THE NEW ZEALAND NATIONAL ENVIRONMENTAL STANDARDS FOR AMBIENT AIR QUALITY: ANALYSIS AND MODELLING CASE STUDY

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Abstract

Historically, the New Zealand rationale behind air quality management has been to adopt an effects-based approach based on environmental impacts. Generally, this method has been efficient in that it permitted emitters to decide how to minimise and mitigate impacts. However, to address the inconsistencies in air quality management across New Zealand born of this approach, and to permit measures designed to improve the working of the Resource Management Act (RMA), National Environmental Standards for Ambient Air Quality have been developed and implemented to establish consistent regulation and protection for all New Zealanders. The standards were gazetted in September 2004, for full implementation by 2013.

This thesis explores the implementation of the National Environmental Standards for Ambient Air Quality, examining the philosophy behind the standards and associated strategies for dealing with air pollution management in New Zealand, and the international context for the development of appropriate tools to address air quality concerns. The research also provides an independent dispersion modelling assessment of the application of the Ministry for the Environment's initiative regarding sulphur dioxide in the Marsden Point airshed, Northland, utilising The Air Pollution Model (TAPM) for a period when heightened concentration values had been recorded.

The key outcomes of the thesis are: (i) 99.9^{th} percentile and maximum values for the simulated two-day modelling case study are within those stipulated by the air quality standards for sulphur dioxide; (ii) modelled concentrations associated with shipping within the airshed of interest contribute significantly to total modelled values; (iii) the chief obstruction to increased use of the prognostic modelling approach is that of the unsatisfactory availability and integrity of emission inventories; (iv) performing long-term high-resolution simulations with multiple point sources is prohibitive due to computational demands; (v) good quality monitoring will always be required; (vi) the standards have broad and far-reaching implications for resource managers, resource users and possibly the economy of individual regions and the country as a whole; (vii) the successful implementation of the National Environmental Standards for Ambient Air Quality in New Zealand will integrate a thorough understanding of modelling, measurements, meteorology and emissions.

1. Introduction

1.1 Introduction

Air quality is a global issue. In many urban centres around the world, particularly in developing countries, deteriorating air quality is a deepening environmental concern. Poor air quality threatens human health and contributes to environmental damage.

In spite of its 'clean-and-green' image, New Zealand suffers from air pollution levels that are considered to present a risk to human health, particularly with respect to PM_{10} (mass of particulate matter less than 10µm in diameter) (MfE, 2002; Spronken-Smith *et al*., 2001; McGowan *et al*., 2002). Air pollution regulation in New Zealand is covered by the Resource Management Act (RMA) 1991, which promotes the sustainable management of natural and physical resources in New Zealand and which requires regional authorities to establish environmental management strategies to address problems of air, land and water quality.

Supported by the powers of the RMA, National Environmental Standards (NES) for air quality were gazetted in New Zealand in September 2004, with those for ambient air quality to come into force on 1st September 2005 and to be fully implemented by September 2013. Where concentrations of the relevant pollutant of interest exceed the standard within a specified regional 'airshed,' the established regulations require that the state of air quality at September 2005 must approach compliance by 2013 via a straight or curved line path. For PM_{10} this means the 24-hour mean concentration must not exceed 50 µg m^{-3} more than once annually within the airshed. This has significant consequences for resource consents, or discharge licences, which will not be granted in a particular airshed if more than one exceedence results in future years. Several New Zealand cities regularly exceed this standard, with Christchurch experiencing 25 to 30 days on which a 24-hour average of 50 µg m^{-3} is exceeded each winter (Sturman & Zawar-Reza, 2005). For the purposes of the regulations, regional airsheds are linked to air quality management policy and have therefore been designated Local Air quality Management Areas (LAMAs). These areas are based on estimated pollutant emissions, meteorological and topographical effects and current observations of pollutants, where available.

Pollution mitigation options designed to attain compliance with the NES in non-compliant airsheds depend on reductions of emissions and a prediction of the effects on concentration levels in the future (Gimson *et al*., 2005). Atmospheric models are increasingly being used to

address air quality management problems that require an understanding of the spatial and temporal variation in air pollution (Zawar-Reza, *et al*., 2005). Models can be used to define airsheds by applying back-trajectories to identify the pathways followed by air during periods of build up of pollution (Sturman & Zawar-Reza, 2002). They may also have applications in long-term epidemiological studies of human exposure to air pollution (Wilson & Zawar-Reza, 2005). In addition, these models can be used to predict future ambient air pollution concentrations in response to a range of different air quality management strategies (Sturman & Zawar-Reza, 2005).

1.2 Thesis structure and overview

This thesis will initially examine the background philosophy behind the establishment of the NES in Chapter 2, looking at air quality management in New Zealand by way of the New Zealand Ambient Air Quality Guidelines and the eventual setting of National Environmental Standards for Ambient Air Quality. The associated instruments used to approach the subject of air pollution governance in New Zealand, such as LAMAs (airsheds) and straight/curved line paths are examined in Chapter 3. Approaches to the development of relevant environmental management tools to address air quality issues internationally are evaluated and compared with the New Zealand experience in Chapter 4.

The research will also undertake an independent analysis of the NES by applying atmospheric dispersion modelling to a selected air quality management area of a Regional Council in order to evaluate progress towards meeting the new standards by the target date of 2013. This work is initially presented via the case-study background and methodology within Chapter 5. Results of the modelling case-study and an introductory evaluation of the results is presented in Chapter 6, whilst Chapter 7 aims to develop the initial interpretations further and link the application of modelling as a tool to help New Zealand Regional Councils achieve their NES objectives. Chapter 8 provides a summary of the previous chapters and offers suggestions for future research.

The specific case study considered by this research utilises The Air Pollution Model (TAPM), a self-contained PC-based model, developed by the Commonwealth Scientific and Industrial Organisation (CSIRO) Australia, which provides a complementary, or in many cases, superior alternative to the Gaussian plume (e.g. Ausplume) or puff (e.g. Calpuff) approaches of recent years. This is particularly true for complex geographical areas or when the available meteorological data are not adequate for predicting air pollution dispersion. TAPM consists of

coupled prognostic meteorological and air pollution concentration components, eliminating the need to have site-specific meteorological observations. Instead, the model predicts the flows important to local-scale air pollution dispersion, such as sea breezes and terrain-induced flows, against a background of larger-scale meteorology provided by synoptic analyses (Hurley, 2002).

Although PM_{10} is the driving force behind the NES, this thesis modelling case-study looks at the only sulphur dioxide (SO_2) limited airshed in New Zealand as a result of the NES, the Marsden Point airshed, Northland. Where other contacted New Zealand Regional Councils were unable to supply data and support for a case-study modelling project, The Northland Regional Council were interested and enthusiastic from the outset, and most interested in the outcomes that a modelling study of SO_2 within the Marsden Point airshed would provide, even though other pollutants, such as particulate matter (PM_{10}) and nitrogen dioxide (NO_2) are also considered to be of concern in the airshed. Performing long-term high-resolution simulations with multiple point sources is also a computationally demanding exercise, and although far from ideal, it was considered appropriate for the purposes of this case-study to concentrate on the main contaminant of concern within the airshed for a limited time period when monitoring data was made available for comparison with the modelling results. These points are a major reason for choosing this particular airshed, the pollutant to be modelled and the extent of the simulation period. It would be impossible however in preceding chapters that discuss the background to the NES, the adopted NES strategies and the international air quality management landscape to ignore PM_{10}, as the vast majority of NES airsheds have PM_{10} as their limiting pollutant, and as PM_{10} has played such an important role in air quality management internationally.

2. Background

2.1 Introduction

Neither air pollution nor efforts to control it are recent phenomena. An early example of pollution control ordinance can be traced to thirteenth-century England, when King Edward I banned the burning of highly polluting coals in London (Schwela, 1997). Despite the early recognition of the adverse effects associated with air pollution, fossil-fuel based transport and industrialisation during and after the industrial revolution led to the sharp rise of air pollution concentrations in many urban areas (Bell, *et al*., 2004). The great black smog of London in early December 1952 had a most severe health impact: approximately 4000 deaths were reported, with the figure quoted as high as 12000 when long-term effects were considered (Bell & Davis, 2001). Also in the 1950's, statistical epidemiological studies began to emerge that would assess the more subtle linkages and associations between air pollution and human health at lower levels of air pollution (Bell, *et al*., 2004), in addition to higher levels of exposure incurred during air pollution episodes such as that experienced in London. As a result, an extensive body of literature on the health and environmental effects of air pollution has amassed and in response countries around the world, including New Zealand, have developed guidelines and standards designed to protect human health and the environment. This chapter reviews the background philosophy behind the establishment of National Environmental Standards for Ambient Air Quality, looking at air quality management in New Zealand by way of the New Zealand Ambient Air Quality Guidelines and the eventual setting of National Environmental Standards for Ambient Air Quality. Background information regarding the contaminant of interest to the thesis modelling case-study, sulphur dioxide, is also introduced and assessed for its' health related effects.

2.2 New Zealand Ambient Air Quality Guidelines

Air quality management in New Zealand has been governed by the introduction of the Ambient Air Quality Guidelines in 1994 by the Ministry for the Environment (MfE), which were revised and updated in 2002. The national ambient air quality guidelines advocated how best to manage air quality under the Resource Management Act (RMA) 1991, and promoted sustainable management of the air resource in New Zealand (MfE & MoH, 2002). The purpose of the RMA is to promote the sustainable management of natural and physical resources in New Zealand, including air. Of particular relevance for air quality management is Section 7(f), which states

that persons exercising powers under the Act must have particular regard to the "maintenance and enhancement of the quality of the environment" (MfE & MoH, 2002).

The guideline values were suggested as being the minimum requirements that outdoor air quality should meet in order to protect human health and the environment. Where air pollution levels breached guideline values, emission reduction strategies were to be implemented to improve air quality. Where levels did not breach the values, efforts were to be made to maintain air quality and, if possible, reduce emissions. The guidelines were formulated following processes and consultation that reflected well-debated, expert, national and international best practice and knowledge. As such, they were to be afforded considerable weight in decision-making on air quality management, but were not legislative requirements under the RMA or any other legislation (MfE & MoH, 2002). Under the RMA, Regional Councils and unitary authorities are responsible for managing discharges into the air and therefore for managing the quality of the outdoor air, and consequently were required to determine the extent to which they would apply the new guideline values and guidance.

The Resource Management Amendment Act 2005 was passed in August 2005. The changes to the RMA were the result of dialogue with local government, industry, environmental organisations and the wider community over an 18-month period. The amendments enabled national environmental standards to be absolute and therefore not be over-ridden by rules or bylaws unless the standard states it may be over-ridden (Wickham, 2005).

2.3 The setting of national standards

In August 2003, the New Zealand Cabinet agreed to the Ministry for the Environment (MfE) undertaking extensive public consultation on a range of proposed air quality standards. Councils, communities and industry throughout New Zealand had called on the Ministry for the Environment to promote consistent and efficient air quality management, and to develop policies that reduced emissions and improved air quality. It was decided that the most appropriate national policy method for achieving such objectives was to implement national environmental standards (MfE, 2003a).

Air quality was identified through working groups as a priority for national standards development for a couple of reasons (MfE, 2003a):

- It was a significant health and environmental issue in New Zealand that required improvement to ensure the sustainability of towns and cities.
- There was sufficient technical and scientific analysis on which to base numerical standards to protect human health.

The setting of formal national standards for ambient air quality aimed to provide a greater impetus for regional and national agencies to implement policies to improve air quality where it was degraded. Standards would support the substantial amount of work already carried out to reduce emissions and improve air quality, and would help drive further improvements where required (MfE, 2003a). Finally, whereas ambient air quality guidelines were not enforceable by law, national standards would harbour the full force of regulation.

Consequently, in October 2003, the Minister for the Environment announced a range of proposed standards including ambient (outdoor) standards for fine particles (PM_{10}), carbon monoxide (CO), nitrogen dioxide (NO_2), sulphur dioxide (SO_2) and ozone (O_3). The proposed ambient standards were based on the existing (non-statutory) ambient air quality guidelines and were developed following a comprehensive review of national and international research and consultation with local government (Regional Councils and unitary authorities). In July 2004, the New Zealand Cabinet Legislation Committee approved the proposed policy and drafting instructions were forwarded to the Parliamentary Council by the Ministry for the Environment the following month. On 6th September 2004, and pursuant to section 43 of the Resource Management Act 1991, Cabinet gazetted the National Environmental Standards (NES) for Ambient Air Quality, with all provisions relating to ambient air standards and consents to come into force on 1st September 2005. Regional Councils and unitary authorities identified forty-two areas where air quality was likely, or known, to exceed the national air quality standards. All but one of the forty-two airsheds contains 'hotspots' where PM_{10} is an issue at certain times of the year. The remaining airshed at Marsden Point Northland also has the potential to exceed the sulphur dioxide standard and is the airshed of prime interest to this thesis.

The principal intent of the ambient air standards is to provide an assured level of protection for the health of all New Zealanders and accordingly they superseded less strict local government controls. The standards also replaced any previous guideline levels and averaging periods, although guideline levels and averaging periods for pollutants not covered by the standards still applied. The standards apply at any place in an airshed that is in the open air and where people are likely to be exposed to the contaminant. However, if the discharge of a contaminant is

permitted by a resource consent (discharge licence), at an industrial site for example, the ambient air quality standard for the contaminant does not apply to the area that the resource consent applies to (MfE, 2005). The justification for this is that acceptable air management procedures are in place and that the consent conditions will require adequate standards compliance. Once the consent expires however, the standard will come into force within the site boundary.

Therefore, the standards apply in the open air wherever people may be exposed over the relevant time averaging period. This includes roadside verges, residential areas, central business districts, parks, beaches, etc. The standards do not apply indoors, in indoor workplace environments, in outdoor workplace environments where the public are not exposed, inside tunnels or inside vehicles (MfE, 2004a).

2.4 Amendments

Amendments to the air quality standards were gazetted in December 2004 and July 2005. The amendments to the standards were made at the request of local government to provide them with greater flexibility in how to reach the agreed goal of meeting the ambient fine particle (PM_{10}) standard by 1st September 2013. The amendments clarified that the restriction on granting of resource consents applied only to significant discharges, and also made explicit provision for the use of offsets. Offsets are mitigation measures, where emissions from a new activity are offset by emission reductions elsewhere within the air quality management area. Examples of offsets can include replacing open fires with cleaner burning alternatives, modernising bus fleets and the fitting of catalytic converters to buses. Allowing a more flexible approach to the management of smaller discharges that may not have a significant effect on levels of PM_{10} within the airshed was also a product of the amendments. Regulation 14 regarding application of the standards was also amended so that industrial sites, which are covered by Occupational Safety and Health (OSH) legislation, were not required to adhere to the standards. For example, a power station discharging SO_2 would not be required to meet the ambient SO_2 limit within their site boundary.

2.5 The standards

From 1st September 2005, Regional Councils and unitary authorities have been required to monitor air quality and publicly report whenever the air in their regions exceeds the standards. The Councils are then expected to make a plan for improvement, showing what they will do to fully comply by 2013. Councils decide how they achieve the targets that the standards set and have the flexibility to focus on the air quality issues in their area that particularly need

improvement. The amendments also permit Councils to choose a straight or curved line path to achieve the relevant pollutant level set for 1st September 2013 via Regulation 17. Table 2.1 lists the New Zealand National Environmental Standards for Ambient Air Quality, as gazetted on 6th September 2004. Units for the standards are in micrograms of pollutant per cubic metre of air ($\mu g\ m^{-3}$) for all contaminants except carbon monoxide which is measured in milligrams per cubic metre of air ($mg\ m^{-3}$). The PM_{10} standard value is averaged over one day. Standard values for sulphur dioxide, nitrogen dioxide and ozone are averaged over one hour and the standard value for carbon monoxide is averaged over an eight-hour period. The sulphur dioxide standard attracts two values. The concentration limit of 350 $\mu g\ m^{-3}$ must be met for all but nine hours each year with none of these hours to be above 570 $\mu g\ m^{-3}$. Allowable exceedences for all pollutants over a 12-month period are also listed in Table 2.1. The ozone standard is never to be exceeded.

2.5.1 Note on units

Units of measurement for the ambient air quality standards are expressed in terms of:

- micrograms ($\mu g = 10^{-6}$ or one one-millionth of a gram) per cubic meter ($\mu g\ m^{-3}$) or milligrams ($mg = 10^{-3}$ or one one-thousandth of a gram) per cubic meter ($mg\ m^{-3}$).
- 1 gram (g) = 1000 milligrams (mg)
- 1 milligram (mg) = 1000 micrograms (μg)
- 1 m^3 = 1000 L

Table 2.1 New Zealand National Environmental Standards for Ambient Air Quality (source: MfE, 2004a).

Contaminant	Standard concentration	Time average	Allowable exceedences per year	Start date
Particles (PM_{10})	50 µg m^{-3}	24-hour mean	One 24 hour period in any 12 month period	1st September 2005
Sulphur dioxide (SO_2)	350 µg m^{-3} 570 µg m^{-3}	1-hour mean 1-hour mean	9 hours in any 12 month period Not to be exceeded	1st September 2005
Carbon monoxide (CO)	10 mg m^{-3}	8-hour running mean	One 8 hour period in any 12 month period	1st September 2005
Nitrogen dioxide (NO_2)	200 µg m^{-3}	1-hour mean	9 hours in any 12 month period	1st September 2005
Ozone (O_3)	150 µg m^{-3}	1-hour mean	Not to be exceeded	1st September 2005

2.6 Sources and health effects

The major sources that emit pollutants and which have been influential in the setting of the NES in New Zealand include domestic (e.g. wood and coal burning heating), industrial (coal or heavy oil power stations), mobile (petrol and diesel cars and trucks), and biogenic or natural (e.g. sea salt, wild fires) sources. Although particles (such as PM_{10} and $PM_{2.5}$) are most commonly associated with health effects, other studies link effects to carbon monoxide, nitrogen dioxide, sulphur dioxide, ozone and hydrocarbons. The types and concentrations of pollutants in the ambient air vary greatly from location to location, with time of day and with season. As these pollutants occur together and are often closely correlated, it has been difficult to clearly identify effects of single pollutants, or potentially damaging combinations of them.

The major pollutants that can produce health effects are the gases sulphur dioxide (SO_2), carbon monoxide (CO), oxides of nitrogen (NOx) and volatile organic compounds (VOCs), as well as solid particulate matter (commonly referred to as particles). Additionally, other gases (such as ozone) and particles (sulphates and nitrates) can form in the atmosphere from reactions involving some of those primary emissions. The health effects of sulphur dioxide, carbon monoxide, nitrogen dioxide, ozone and particles are reported in Denison *et al*. (2000) (Fisher *et al*., 2007).

2.7 Sulphur dioxide properties

The thesis modelling case-study investigates the only sulphur dioxide (SO_2) limited airshed in New Zealand as a result of the NES, the Marsden Point airshed, Northland. Sulphur dioxide is a colourless, water-soluble gas that is reactive and has a pungent odour and is detectable to the human nose at concentrations of around 0.5 - 0.8 parts per million (1329 - 2126 µg m^{-3}). Concentrations of SO_2 in ambient air typically occur as a result of combustion processes, in particular the burning of high sulphur fuels, although specific industries such as fertiliser manufacturing also discharge SO_2. Sulphur dioxide is subject to a series of transformation processes in the atmosphere, which can result in sulphurous and sulphuric acids, sulphites and sulphates being formed (MfE, 2004b). The physical and chemical properties of sulphur dioxide are summarised in Table 2.2.

Table 2.2 Physical and chemical properties - sulphur dioxide

Molecular formula	SO_2
Molecular weight (g mol^{-1})	64.06
Physical properties	Colourless gas. Strong, suffocating odour. Melting Point (°C): -75.51 Boiling Point (°C): -10.06 Specific Gravity: 0.00293 Vapour Density: 2.26
Chemical properties	Non-flammable gas. Sulphur dioxide may oxidise to sulphur trioxide which then dissolves in water to produce sulphuric acid.
Chemical structure	

2.7.1 Health effects of sulphur dioxide

Sulphur dioxide causes its irritant effects by stimulating nerves in the lining of the nose and throat and the lung's airways. This causes a reflex cough, irritation and a feeling of chest tightness, which may lead to narrowing of the airways. This latter effect is particularly likely to occur in people suffering from asthma and chronic lung disease, whose airways are often inflamed and easily irritated (Department of Environment, 1995). Asthmatics are generally considered the most sensitive group in the community to concentrations of SO_2. Other sensitive groups include those exercising. This is because SO_2 is very reactive and consequently the distribution of SO_2 along the conductive airways of the respiratory tract is non-uniform, depending on breathing volumes and types. For nasal breathing with low to moderate volumes, the penetration into the lungs is negligible. For oral inhalation and larger volumes, doses may reach the segmental bronchi (WHO, 1996).

The health effects of concentrations of SO_2 have been studied in a number of ways including exposure of volunteers to sulphur dioxide in the air they are breathing in a laboratory situation, and by examination of the effects on members of the population who have been exposed to episodes of atmospheric pollution. In the controlled laboratory situation, acute responses occur within the first few minutes of exposure and further inhalation does not increase effects (MfE, 2004b).

Results of air quality monitoring would suggest that there are unlikely to be major health impacts associated with SO_2 exposure in New Zealand as concentrations in most areas are well below the ambient air quality guideline and standard values. Some exceptions may occur on occasion in localised areas if significant industrial SO_2 concentrations exceed approximately 500 $\mu g\ m^{-3}$ (10-minute average) (MfE, 2004b). As the only SO_2 limited airshed in the country following promulgation of the national air quality standards, the Marsden Point airshed is possibly one such exception.

2.8 Summary

The setting of national air quality standards for sulphur dioxide, PM_{10}, carbon monoxide, nitrogen dioxide and ozone has been born out of the desire to promote consistent and efficient air quality management and to develop policies that reduce emissions from a variety of sources to subsequently improve air quality in New Zealand. The National Environmental Standards for Ambient Air Quality came into effect on 1st September 2005, apply nationally and are enforceable by law. The Marsden Point airshed in Northland is the only sulphur dioxide limited airshed resulting from the implementation of the standards and is the focus of the thesis modelling case-study to be introduced in Chapter 5. Regional Councils have the responsibility of monitoring air quality, reporting exceedences and achieving the standards by September 2013. Regional Councils were also charged with the task of developing and advising airsheds within their region where the ambient air quality standards were currently being exceeded or were likely to be exceeded, and for also projecting how the Regional Council would attain compliance with the standards. It is this topic, the tools used by Regional Councils to improve air quality in a particular airshed, which will be the focus of Chapter 3.

3. NES instruments

3.1 Introduction

The ambient air quality standards came into force on 1st September 2005. The two most demanding implementation issues facing Regional Councils prior to this date were:

1. Gazetting regional airsheds or local air management areas (LAMAs)

2. Developing straight line paths (SLiPs) or curved line paths (CLiPs) for assessing compliance with the standards for 2005 and beyond.

This chapter reviews the above mentioned tools for dealing with air pollution management in New Zealand, including how LAMA categories have been defined in order to link the implementation of the standards to the delimitation of airsheds, plus the issue of Regional Council projected routes to compliance via the 'straight-line path' or 'curved-line path' by 1st September 2013.

3.2 The LAMA - definition of 'airshed' for the purposes of the new regulations

Following amendments to the air quality standards in July 2005, the definition of an airshed was clarified as a region of a Regional Council. It was also made clear that where a Gazette notice specifies a part of a region as a separate airshed, the remainder of the region is still an airshed.

Ideally, in an air quality context, an airshed should be defined by an almost physical boundary through which no pollution travels (and in some small valleys this may be close to reality). However, in practice the wind is capable of moving pollution large distances (the single largest exceedence of PM_{10} in Auckland in 2002 was due to Sydney bushfires). Thus, there is some form of subjective judgment to be made as to how much cross boundary transfer is acceptable before the airshed boundary needs to be extended (Fisher *et al*., 2005a).

The regulations attached monitoring, reporting, and consent decision requirements to airsheds. In this context, the term 'airshed' as used in the regulations is more likened to an 'air quality

management area,' rather than a strictly science based concept of an airshed (although in many instances the two are equivalent) (MfE, 2004a). Given the above, the term 'Local Air Quality Management Area' or 'LAMA' was adopted by the National Air Quality Working Group in December 2004 for the purposes of implementing the air quality standards. The following definition was put forward:

> A local air quality management area (LAMA) is an area where it can be practicably shown that emissions in one part have an effect on key contaminant concentrations (normally PM_{10}) in other parts, over the time period of interest (normally 24 hours), and on a long term basis. (Fisher *et al*., 2005a).

The PM_{10} standard is the driving force behind the definition of an NES airshed, as the vast majority of airsheds have PM_{10} as their limiting pollutant. Also, with consideration to the financial implications of regulatory monitoring requirements which are tied to individual airsheds, larger rather than smaller airsheds would be sought.

According to the implementation guidelines (MfE, 2004a), LAMAs are:

- Designed to be practical as administrative/management tools
- Large (3-9 per Council)
- Based on geophysical airshed criteria (i.e. with consideration to topography and airflow)
- Designed to interact with other planning and management processes
- Reviewable
- Categorised

LAMAs are not:

- Airsheds in the strict geophysical sense (although in many cases they will be)
- Small areas around problem sources

Local governments were invited to advise the MfE of their selected LAMAs where the ambient air quality standards were currently being exceeded or were likely to be exceeded. The Northland Regional Council advised that the Marsden Point airshed should be gazetted following a thorough review of sulphur dioxide monitoring results and dispersion modelling to forecast future levels of sulphur dioxide in the area.

3.2.1 LAMA categories

Based on the use of objective criteria, three categories of LAMA were selected in order to link the implementation of the standards to the delimitation of airsheds. Key inputs used as guides in the determination of LAMAs were topography and airflow boundaries, emissions inventories, local weather and the presence of major industrial emitters. Political and administrative boundaries were also areas of consideration.
The following LAMA categories were established:

- Category 1: Areas where exceedences currently occur or are likely to occur without mitigation actions, therefore requiring enhanced air quality management.
- Category 2: Areas where the ambient concentration is currently expected to be, or is likely to be above 66% of the standard.
- Category 3: Areas that do not currently, or are unlikely to in the near future, produce ambient concentrations greater than 66% of the standard.

The Ministry for the Environment was to be notified by Regional Councils of their regions' proposed airsheds by 1st July 2005, for gazettal by the Minister. The airsheds were gazetted in August 2005.

3.2.2 Emissions versus concentrations

LAMAs are defined essentially by patterns of emissions (except for geophysical, weather and dispersion factors), and mitigation measures based on emissions reduction policy, yet the NES are based on extreme concentrations. The link between concentrations and emissions can be provided through predictive dispersion modelling. There has been debate over whether LAMAs should be defined in terms of emissions or concentrations (Gimson *et al*., 2005).

According to Fisher *et al*. (2005b), concentrations of contaminants in ambient air at a given location in an airshed depend on:

• **where** the sources are located (both horizontally and vertically, effect of terrain);
• **how much** the sources emit (emissions);
• **when** the sources are active (both time of day and time of year);
• what the **weather** is doing (calm, windy, temperature inversions).

Demographic changes, technology evolution, transport patterns and industry consent changes are other areas requiring consideration. Of these, information about the size and location of source

emissions is generally the easiest to estimate using regional or national air emissions inventories. As a consequence, emissions can be used as a proxy for concentrations with the following proviso:

> Ambient concentrations depend on a number of factors including emissions, but the relationship between concentrations and emissions may not be precisely linear. This means that a 30% reduction in concentration might only be achievable with a greater than 30% reduction in emissions. Therefore, if emissions are to be used as a proxy then some safety margin needs to be built in to the future predictions to ensure compliance with the standard in future years (Fisher *et. al.,* 2005b).

3.2.3 When is a LAMA not a LAMA?

Apart from the debate over whether LAMAs should be defined in terms of emissions or concentrations, it is also interesting to note that calling an airshed a LAMA or vice versa is not necessarily as straight-forward as one may hope. As previously mentioned, the term 'airshed' as used in the regulations is more likened to an 'air quality management area,' rather than a strictly science based concept of an airshed (although in many instances the two are equivalent). In one particular document released on the topic of the NES, it is written: "In this discussion document airsheds and LAMAs are considered to be synonymous but, from this point on, the word 'airshed' is used in preference to be consistent with the NES Regulations." (Fisher *et al.*, 2005b)

Figure 3.1 shows the gazetted Local Air Quality Management Areas for the New Zealand NES for Ambient Air Quality at 1st September 2005. Table 3.1 lists the airsheds by notice in the New Zealand Gazette at the same date plus those for the Otago region gazetted in December of the same year and those amended and gazetted in 2007 for the Waikato and Auckland regions. These airsheds were designated through recommendations by Regional Councils and unitary authorities to the Minister. Airsheds and their boundaries were drawn by Councils using existing knowledge of air quality in the region, the location of significant sources and the effects of topography (hills and valleys) and climate on the dispersion of pollution. They extend upwards from ground level, with no specified upper limit, including coastal marine areas. In most cases they represent areas where it is known, or likely, that the fine particle ambient standard is exceeded. The exception to this is the Marsden Point airshed, Northland, which is based on sulphur dioxide. It is possible that airsheds may be amended. Councils (and/or the Minister) may wish to change boundaries or notify new airsheds due to changing circumstances over time (MfE, 2005). No airsheds have been gazetted in the Taranaki and Gisborne regions.

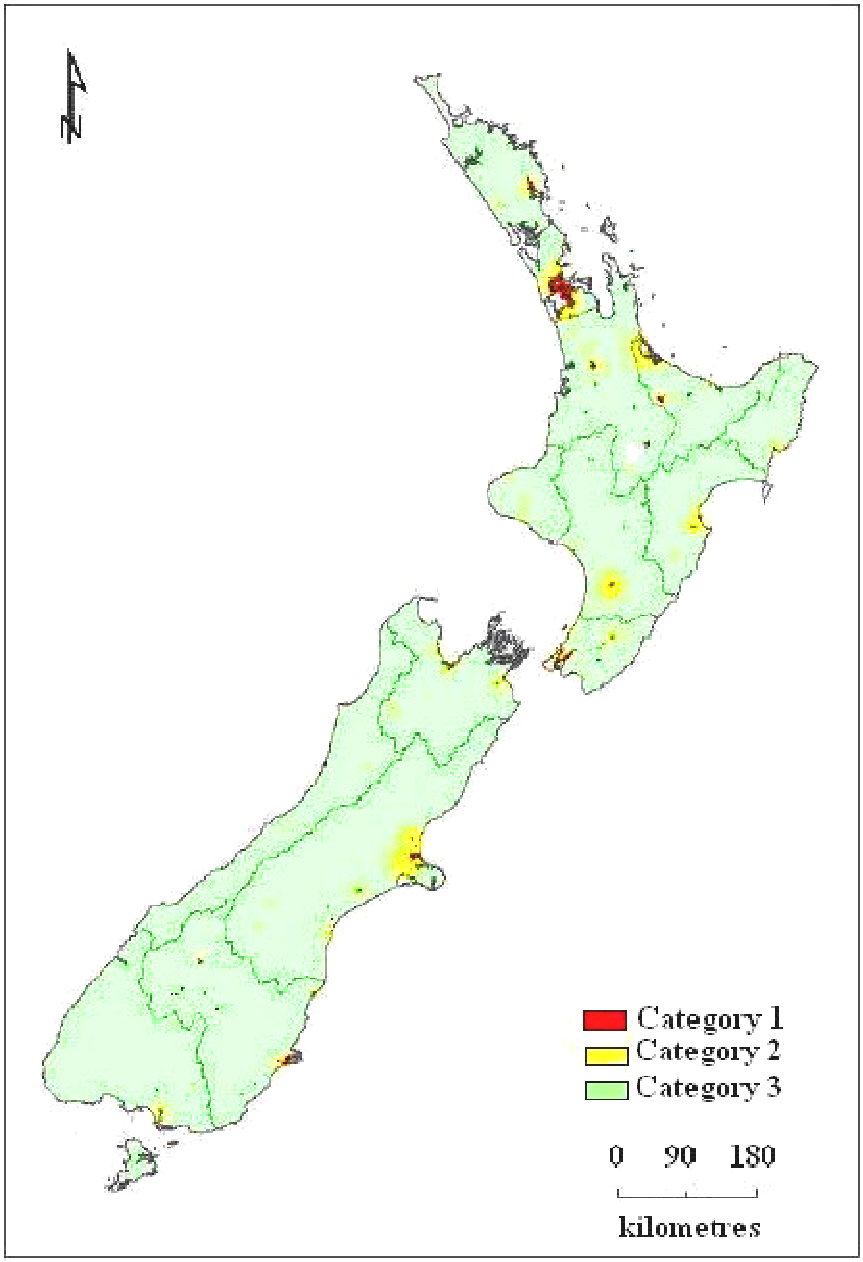

Figure 3.1 **Local Air Quality Management Areas (airsheds) - New Zealand NES for Ambient Air Quality. Category 1: red - 60 areas designated for enhanced air quality management, which are the recommended 'airsheds' under the new regulations. Category 2: yellow - 85 areas for review and assessment. Category 3: green - rest of country unlikely to experience problems. (source: Fisher *et al.,* 2005a).**

Table 3.1 Airsheds gazetted for New Zealand at 1st September 2005, except for Otago (8th December 2005), Waikato (15th March 2007) and Auckland (31st May 2007) regions (sources: *New Zealand Gazette*, No. 141 - 25/8/2005, No. 204 - 8/12/05, No. 30 - 15/3/07 and No. 58 - 31/5/2007).

Region	Airshed	Stationary Office Number
Auckland	Greater Auckland - Auckland urban - North Shore - Whangaparoa Beachlands Helensville Kumeu Maraetai Pukekohe Riverhead Snells Beach Waiheke Island Waiuku Warkworth Wellsford	 357967 357966 357965 381998 382006 382000 381999 381996 382001 382003 381995 381997 382004 382005
Bay of Plenty	Rotorua	358012
Canterbury	Christchurch Timaru Kaiapoi Rangiora Ashburton Geraldine Waimate	357116 357117 357119 357120 357121 357122 357123
Gisborne	None	-
Hawkes Bay [a]	Napier Hastings	357899 357899
Manawatu/Wanganui	Taihape Taumarunui	356024 356027
Marlborough	Blenheim	356009
Nelson	Nelson South Tahunanui – Stoke Nelson City	356467 356468 356471
Northland	Kerikeri Kaitaia Marsden Pt Whangarei	356455 356457 356458 356459

	Dargaville	356466
Otago	Airshed 1 - Alexandra - Clyde - Arrowtown - Cromwell - Roxburgh - Naseby - Ranfurly Airshed 2 - Mosgiel - Palmerston - Green Island - South Dunedin - Milton Airshed 3 - Oamaru - Balclutha - Central Dunedin - North Dunedin - Waikouaiti - Port Chalmers Airshed 4 - Kingston - Queenstown - Wanaka - Hawea	 361008 361031 361012 361015 361011 361028 361026 361013 361023 361010 361017 361021 361009 361014 361016 361020 361035 361018 362447 362448 362450 362451
Southland	Gore Invercargill	355699 355700
Taranaki	None	-
Tasman	Richmond	355934
Waikato	Hamilton City Taupo SO Turangi Tokoroa Putaruru Te Kuiti Matamata Morrinsville Te Aroha Cambridge Te Awamutu and Kihikihi Huntly Ngaruawahia Otorohanga Paeroa	378461 378482 378502 378491 378480 378487 378465 378467 378483 378457 378485 378462 378469 378474 378479

	Waihi Whangamata Whitianga Thames Tuakau	378505 378503 378456 378490 378501
Wellington	Kapiti Coast Karori Lower Hutt Porirua Upper Hutt Wainuiomata Wairarapa Wellington	355936 355937 355941 355942 355943 355944 355945 355946
West Coast	Reefton	356571

Note: These airsheds may change through subsequent gazetting.
[a] Hawkes Bay has two designated airsheds (Napier and Hastings) with detail provided on one map.

3.3 SLiPs and CLiPs - Straight Line Paths and Curved Line Paths

According to the regulations, either a straight line path (SLiP) or a curved line path (CLiP) must be developed for any airshed in a region in which the concentration of the limiting pollutant breaches the standard.

For sulphur dioxide, the 1-hour mean concentration must not exceed 350 µg m^{-3} more than nine times in a 12-month period and never exceed 570 µg m^{-3}. However, only one exceedence is recorded when exceedences at two or more sites in the same airshed occur for the same time period. Therefore a SLiP or a CLiP must be developed for any airshed in a region where the limiting pollutant concentration breaches the standard at any time.

According to Regulation 17(b) of the NES amendments (MfE, 2005), a CLiP can only be used in preference to a SLiP if the CLiP has been outlined in the regional plan and if there are rules that ensure that an application for a resource consent is declined for applications that are likely to cause, at any time, the concentration of the limiting pollutant in the airshed to be significantly above the CLiP.

According to Fisher *et al*. (2005b), there are three key parameters that need to be used to ensure compliance with the NES:

- The target air quality represented by the SLiP or CLiP according to the Regulations (related to either the number of exceedences or the corresponding maximum concentration).
- The observed air quality represented by the monitoring data (related to either the number of exceedences or the corresponding maximum concentration).
- The predicted air quality based on current and future management strategies (related to the emissions).

3.3.1 Definitions of SLiPs and CLiPs

Straight line paths (SLiPs) are defined in the NES amendments (MfE, 2005) under Regulation 17 subclause (5) as:

> A straight line that –
> (a) starts on the y-axis of a graph at a point representing, as at the relevant date, the extent to which the concentration of the limiting pollutant in the airshed breaches its ambient air quality standard; and
> (b) ends on the x-axis of the graph at a point representing, as at 1st September 2013, the ambient air quality standard for the limiting pollutant in the airshed.

The relevant date means –

(a) in the case of an airshed that is represented by the whole region under the responsibility of a regional Council, 1st September 2005;

(b) in the case of an airshed that is part of the region of a Regional Council, the date of the notice in the Gazette that specifies the part to be a separate airshed.

Curved line paths (CLiPs) are defined in the NES amendments under Regulation 17 subclause (5) as:

> A curved line that –
> (a) starts on the y-axis of a graph at a point representing, as at 1st September 2005 or the date that the plan is publicly notified (whichever is the later), the concentration of the limiting pollutant in the airshed; and
> (b) ends on the x-axis of the graph at a point representing, as at 1st September 2013, the ambient air quality standard for the limiting pollutant in the airshed.

The SLiP and an example of a CLiP are illustrated below in Figure 3.2. In addition to these projected paths to compliance, Regional Councils will be able to plot their observed path to compliance over time (i.e. a plot of monitored concentration versus time).

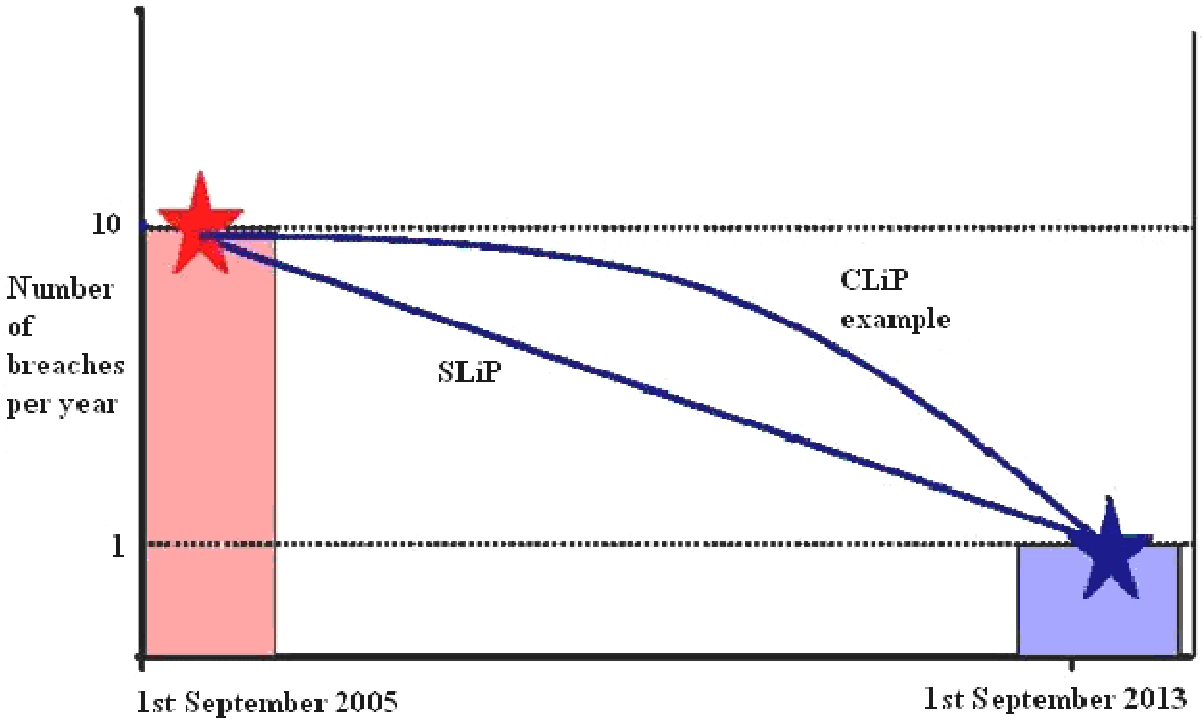

Figure 3.2 Straight Line Path (SLiP) and Curved Line Path (CLiP), based on example given in Fisher *et al.* (2005b).

3.3.2 The setting of SLiPs and CliPs

Effective regional management of air quality to meet the national air standards requires reliable predictions of future air quality. Such predictions are themselves dependent on emissions inventories and modelling. Certain tools have been used by Regional Councils in setting of straight and curved line paths in order to meet the requirements of the NES. According to Fisher *et al*. (2005b), the six basic tools are:

- Emissions Inventories: How much material is being emitted, where and when.
- Modelling: How the material is transported around the region and where it ends up.
- Monitoring: Measurements to confirm and validate modelling and assessments.
- Geophysical Information (including meteorology): locations, hills, valleys, weather.
- Growth Projections: changes in population, industrial development, vehicle use.
- Emissions Factors: rates of emissions and how these might change in future.

3.4 Summary

A gazetted airshed, or for the purposes of the Regulations, a Local Air Quality Management Area, is a specific area identified by a Regional Council where the air quality standards are (or may be) breached. These areas have been publicly notified via the New Zealand Gazette and are known as gazetted airsheds. Small airsheds exist in some regions whereas other regions possess larger geographic areas as their gazetted airsheds, which is simply a product of the approach taken by each Regional Council in defining their airsheds. The SLiP and CLiP essentially refer to lines on a graph that plots the limiting pollutant of the airshed over time. The form of the path is determined by the state of the air quality when the ambient air quality standards came into force on 1st September 2005 and the rate at which things must improve to achieve compliance by 1st September 2013. The air quality standards and associated tools and strategies for dealing with air pollution management in New Zealand have been developed following an extensive review of national and international research. In the following chapter, the approaches to the development of relevant environmental management tools to address air quality issues internationally are evaluated and compared with the New Zealand experience.

4. International context

4.1 Introduction

Air-quality guidelines/standards have been set in many parts of the world. As in New Zealand, the main aim of these is the protection of human health, but in some cases it is also the protection of public welfare (e.g., visibility and damage to buildings) and effects on vegetation. Over recent years, within various jurisdictions, there have been fairly consistent trends in the reviews of existing guidelines/standards (Denison *et al.,* 2000).

The process of setting an air quality standard involves a range of environmental, health, technical, social, economic, political, legislative and cultural considerations (NEPC, 2002). New Zealand, with its relatively clean air environment, has the luxury to take a fairly pure stance, and establish air quality guidelines/standards based almost solely on health and environmental considerations (MfE, 2000).

A trend in international guidelines/standards is the use of such concepts as lowest observed effect level, lowest observed adverse effect level, no observed effect level and no observed adverse effect levels, along with the application of uncertainty factors. The World Health Organisation (WHO) has proposed that for those contaminants for which thresholds for the onset of health effects do not appear to exist, a risk based approach be used. Unit risks, based on risk estimates from time-series studies, have long been associated with carcinogenic compounds, but the concept has recently been applied to particles (but not to ozone and lead, two contaminants which similarly do not have apparent threshold concentrations) (MfE, 2000). Methodological principles of the procedure and scientific basis for the risk estimates are summarised in the World Health Organisation documents: 'Quantification of health effects of exposure to air pollution' (WHO, 2000), and 'Health aspects of air pollution with particulate matter, ozone and nitrogen dioxide.' (WHO, 2003).

The area of greatest change has been in the setting of particle guidelines/standards. The first standards were based on total suspended particulates (TSP), which included all particles with an aerodynamic diameter less than about 75 µm. Since that time there has been an overwhelming body of literature relating adverse health effects to PM_{10}, particles with an aerodynamic diameter less than 10 µm. These studies have resulted in air-quality standards being set for PM_{10} aimed at the protection of human health. The approaches taken in the setting of PM_{10} standards by various

countries have differed significantly, and this has led to a wide range of air quality standards (Denison *et al.,* 2000). Methodologies are often unique to the particular country and somewhat more complex and established than that in New Zealand. Various designs can permit allowable exceedences, different zones where different standards apply, broadcasting of standards several years in advance and emissions standards rather than or in addition to ambient standards. This chapter will now look at five overseas examples where environmental management tools have been developed to address air quality issues. The influences on the designation of air quality management areas, internationally compared with New Zealand, are also considered.

4.2 Australia

The Australian National Environment Protection Council, in 1998, set health-based ambient air quality standards for six pollutants - carbon monoxide, nitrogen dioxide, photochemical oxidants like ozone, sulphur dioxide, lead and particles as PM_{10}. In May 2003, the National Environment Protection Council varied the Ambient Air Quality National Environment Protection Measure to include advisory reporting standards for particles as $PM_{2.5.}$ The standards were based on an assessment of the scientific and medical literature available at the time.

The 10-year goal of the Ambient Air Quality National Environment Protection Measure specifies that by 2008 the short-term standards for CO, NO_2, O_3 and SO_2 can be exceeded on only one day per year, and the PM_{10} standard can be exceeded on only five days per year. With the making of the Ambient Air Quality National Environment Protection Measure, each jurisdiction (state) was required to develop and submit a plan specifying monitoring to be carried out for National Environment Protection Measure purposes, according to the required protocol. Considerable effort has gone into the networks to ensure that the resulting data are nationally consistent.

Compliance with the standards will result from measurements made at designated 'performance monitoring stations.' Monitoring and reporting formally commenced in the year 2002 and covered 79 sites where one or more of the seven ambient air quality pollutants are monitored. Almost all of these sites are in major urban areas, mostly in the capital cities. However, with the gazetting of the standards, data from smaller regional centres has also become available (DEH, 2004). Data collection of emissions has been carried out following the development of jurisdictional monitoring plans, which were approved in June 2001. Hourly data for CO, NO_2, O_3, SO_2, PM_{10} (TEOM) and $PM_{2.5}$ (TEOM), daily data for PM_{10} (HiVol) and Pb, and metadata containing current and historical information about monitoring sites has been collected. The Tapered Element Oscillating Microbalance (TEOM) is a particulate material monitoring device

which has a small pump that sucks air through a filter at a constant rate. The weight of the filter changes with more or less PM_{10} in the air, and this in turn changes the frequency of a small vibrating element in the machine. The TEOM calculates the amount of PM_{10} from the changed vibration. A high volume particulate sampler (HiVol) samples air by drawing it at a specified flow rate through a glass-fibre filter paper mounted beneath a protective hood to prevent material falling directly onto the paper. Each sample is weighed in a temperature and humidity controlled environment and the mass of the unexposed filter paper subtracted to determine the mass of sample collected.

The National Environment Protection Measure provides for surrogates for monitoring, such as emission inventories and modelling, to be used for assessing air quality against the standards. Together with mobile monitoring, these methods may be used to confirm the locations of future performance monitoring stations and screen sub-regions (EPA Vic, 2001).

The desired environmental outcome of the standards is to achieve the goal as assessed in accordance with the monitoring protocol by 2008. Jurisdictions are required to report annually on progress towards achieving the goal, although for all years prior to 2001 there was no requirement to report against the standards.

Air quality in Australia can be affected in several ways, each of which can have a negative effect on emissions compliance with the standards. Adverse effect from drought related dust storms and bushfires can lead to numerous exceedences of the particles standard and contribute to exceedences of the ozone standards. As a result, for many jurisdictions the standards to the extent specified are being met for all pollutants except particles (as PM_{10}) and ozone in the years since reporting began in 2002.

4.3 Great Britain

The designation of air quality management areas is a statutory requirement of air quality legislation in Great Britain, where specific air quality objectives are predicted to be exceeded by certain target dates (Beattie *et al*., 2001). Local government in Great Britain is responsible for the implementation of the Local Air Quality Management (LAQM) elements of the Air Quality Strategy for England, Scotland, Wales and Northern Ireland, which superseded the National Air Quality Strategy. The Air Quality (England) Regulations 2000, and those of the other UK devolved administrations, specify air quality objectives for seven pollutants, which include nitrogen dioxide, PM_{10} and sulphur dioxide. Local authorities in England, Scotland and Wales

(i.e. Great Britain) have a duty to work towards achieving the objectives which are health-based and allow for considerations of cost and benefit, feasibility and overall practicability of achieving a particular level of air quality (Woodfield *et al*., 2002a).

Following a scientific air quality review and assessment process, involving air quality modelling and monitoring tools and techniques to predict locations where the air quality objectives may be exceeded (Elsom & Crabbe, 1996), local authorities were required to declare air quality management areas in locations where such exceedences are predicted (DETR & National Assembly for Wales, 2000). Air quality is spatially inhomogeneous, as is the location of high concentrations of air pollution and such locations may be thought of as hot spots. The identification of such pollution hot spots is therefore focused on locations where the public might reasonably be expected to be exposed (DETR & National Assembly for Wales, 2000), and the air quality management process is thus receptor-based in its approach. The concept of air quality management areas in Great Britain is therefore similar to that of the Local Air Quality Management Area (LAMA) developed in New Zealand. At the start of 2002, 124 local authorities had declared or anticipated declaring air quality management areas. (Woodfield *et al*., 2003).

Of the local authorities requiring an air quality management area, 65% used an advanced dispersion model to identify potential exceedences and to base boundary decisions upon (Woodfield *et al*., 2000). A significant proportion of local authorities declaring air quality management area (93%) used a combination of continuous monitoring and advanced modelling tools to identify potential exceedences (Woodfield *et al*., 2002a), and the majority have used advanced modelling tools for this purpose, with a minority relying upon less sophisticated tools.

A variety of approaches for both identifying locations of predicted exceedences and the subsequent designation of air quality management area have emerged in the first phase of air quality assessment in Great Britain. The variability in modelling techniques used and consideration of uncertainty in determining air quality management areas has resulted in inconsistencies in the decision-making processes across various local authorities across England, Scotland and Wales. As a result, some locations that have required an air quality management area have not been designated, and other locations have been declared through an overly cautious approach. This has caused concern for local authorities involved in the assessment process (Woodfield *et al*., 2002b). Greater consistency in the approach to modelling, model accuracy and

use of uncertainty and error in determining air quality management areas would assist in alleviating such concerns (Woodfield *et al*., 2002a).

As part of the European Union, Great Britain is also required to meet European Union air quality laws. Air pollution in many of London's busiest streets is well over twice the maximum level required by European Union law and becoming worse, mainly due to emissions from road traffic (Birkett, 2008). A Congestion Charge scheme for traffic in central London is one measure that has been introduced to aid in meeting European Union air quality laws.

4.4 European Union

Air pollution results in several hundreds of thousands of premature deaths in Europe each year, increased hospital admissions, extra medication, and millions of lost working days. The health costs to the European Union are huge. While the environmental damage through acidification of ecosystems and damage to crops and forests is impossible to quantify, it is likely to be substantial as well. The pollutants of most concern for human health are airborne particulates and ozone (Commission of the EU Communities, 2005).

Clean Air for Europe was launched in March 2001. This is a programme of technical analysis and policy development that underpinned the development of the Thematic Strategy on Air Pollution under the Sixth Environmental Action Programme. The Commission adopted the Thematic Strategy on 21st September 2005. The aim of the programme was to develop a long-term, strategic and integrated policy to protect against significant negative effects of air pollution on human health and the environment, and to review current policies and assess progress towards long-term objectives. It established five working groups to provide assistance and advice (Commission of the EU Communities, 2005).

An overriding principle of the programme was to ensure that the analyses were conducted on the basis of the best available information. It is for this reason that the main analytical tools (the Regional Air Pollution Information and Simulation (RAINS) model, and cost-benefit methodology) were both subject to independent peer-review before being used to develop and analyse policy scenarios. In addition, the World Health Organisation was asked to provide its best information on the impacts of air pollutants on health.

The programme concentrated on a variety of air pollutants - sulphur dioxide, oxides of nitrogen, ammonia, volatile organic compounds and particulates. The objectives and indicators developed

on the basis of scientific evidence have served to set binding air quality thresholds, provide targets for sectoral and source-specific strategies and provided tools for informing the public and policy-makers at all levels of government. These tools have been supplemented by the development and validation of harmonised emission inventories, air quality assessments, emission and air quality projections, cost-effectiveness studies and integrated assessment modelling.

The European Environment Agency and Eurostat (European Statistics) have developed indicators to monitor the impacts of air emissions on human health and the environment, and there will be long-term monitoring under the United Nations Economic Commission for Europe Convention on Long-range Transboundary Air Pollution. Monitoring, modelling, assessment and mapping will follow agreed methodologies. As community air pollution policy is built on robust scientific and technical knowledge, further research will be needed to refine current and future policies and measures. As the understanding of adverse health and environmental impacts improves, it will be important to keep targets and policies under review and to take account of changes in the costs and effectiveness of measures. The Commission plans to carry out a first review in about five years from the adoption of the Strategy (i.e., 2010) (Commission of the European Union Communities, 2005).

4.5 United States of America

The U.S. federal government's first major efforts in air quality legislation began in 1955 with the Air Pollution Control Act. In 1970, two landmark events took place that helped to establish the basic framework by which air quality is managed in the United States. These events were the creation of the U.S. Environmental Protection Agency and the passage of the Clean Air Act Amendments of 1970. This framework was further developed and refined with the passage of the Clean Air Act Amendments of 1977 and 1990. Since passage of the Clean Air Act Amendments of 1970, the nation has devoted significant efforts and resources to air quality management, and substantial progress has been made (USNRC, 2004).

In 1971, national air quality standards were established for the first time for six criteria pollutants: carbon monoxide, nitrogen dioxide, sulphur dioxide, total suspended particulate matter, hydrocarbons, and photochemical oxidants. Lead was added to the list in 1976, photochemical oxidants were replaced by ozone in 1979, and hydrocarbons were removed in 1983. In 1987, the definition of suspended particles as a criteria pollutant was also changed. Total suspended particulates was revised to include only particles with an equivalent

aerodynamic particle diameter of less than or equal to 10 μm (PM_{10}), and was further revised in 1997 to include a separate standard for particles with an equivalent aerodynamic particle diameter of less than or equal to 2.5 μm ($PM_{2.5}$).

The Clean Air Act provides a legal framework for promoting public health and public welfare by pursuing five major air quality goals, which has included the establishment by the U.S. Environmental Protection Agency of maximum allowable atmospheric concentrations of the six major criteria pollutants, designated as the National Ambient Air Quality Standards.

In areas designated not to be in attainment with the standards, individual states have developed state implementation plans that use modelling tools to develop and evaluate various control strategies and show, with the assistance of national control programmes, how they will meet the standards. State implementation plans for the 1997 standards will be due in 2007-2008. States have five years from their non-attainment designation date to reach attainment, or the State may request a five-year extension. If an extension is granted, the State will need to demonstrate that Reasonable Further Progress is being made toward attainment, which also requires the use of modelling tools. This requirement is similar to that of the New Zealand NES, where concentrations of the limiting pollutant exceeding the standard within a specified regional airshed at September 2005 must display compliance by 2013 via a straight or curved line path.

The standards have been developed via monitoring, analysis, research and development. Monitoring has provided the data necessary to determine trends in emissions, air quality, and various health and ecosystem outcomes. Such observational data have been essential for determining the effectiveness of regulations and assuring compliance, providing valuable input to air quality models, and supporting long-term health and ecosystem assessments. In addition, the data are used by the scientific research community. Analysis activities have provided critical information to air quality managers who use model results, risk assessments, and economic and other analyses to better characterise their air quality problems and the impacts of various control strategies. Finally, research and development efforts furnish advances in the fundamental understanding of the science and impacts of air pollution, the instruments needed for monitoring, and the technology available for controlling emissions (USNRC, 2004).

The National Exposure Research Laboratory is one of three national laboratories that conduct research for EPA's Office of Research and Development. This laboratories research supports both the National Ambient Air Quality Standards development and implementation processes

and also serves to integrate the two processes. The research also supports the development and evaluation of State Implementation Plans and Reasonable Further Progress demonstrations by providing atmospheric modelling tools to: 1) predict the impact of various control strategies on future air quality levels; and 2) identify the relative source contributions of atmospheric measurements. The Community Multiscale Air Quality modelling system predicts air quality by combining emissions inputs with atmospheric chemistry and meteorology. The National Exposure Research Laboratory also develops and applies receptor modelling techniques that can be used to more effectively target the sources of air pollution (NERL, 2005).

The goal of the National Ambient Air Quality Standards development and implementation processes is to improve public health and protect the environment. Following individual states development and implementation of state plans to reach attainment, an improvement in public health and the environment is anticipated, but not ensured. As a result, the U.S. Environmental Protection Agency programme includes a component designed to measure the effectiveness of the Agency in achieving the anticipated public health and environmental improvements (NERL, 2005). A review of the National Ambient Air Quality Standards is expected during the years 2010 and 2015.

4.6 China

Urban air pollution is one of the most visible environmental problems in rapidly developing China. The predominant ambient air pollutant in Chinese cities is suspended particulate matter, about 60 percent of which is PM_{10}, the main source of associated health problems. As a consequence, reducing ambient fine particulate concentration levels should be the centre of attention in China's urban air pollution control agenda (World Bank, 2001). The most common airborne fine particles in China are sulphates emitted from coal combustion, which are aerosols converted from sulphur dioxide when condensed in the atmosphere (Chaoyang *et al*., 2002).

High ambient concentrations of ground level emissions cast a hazy veil over the urban landscape and cause alarming damage to public health. According to Chaoyang *et al*. (2002), two out of three cities in China fail to meet the residential ambient air quality standards, resulting in large population exposure to health risks such as chronic bronchitis, pulmonary heart disease and lung cancer. Respiratory diseases are a leading cause of premature deaths in China. The World Bank (1997) estimated that air pollution cost China's economy more than 7 percent of GDP in 1995, largely in health damage. In 1999, only one third of China's 338 monitored cities were in compliance with the nation's residential ambient air quality criteria (World Bank, 2001).

China has progressively built its capacity in air pollution management. The Chinese government has constituted laws in the field of ambient air protection, promulgated standards for ambient air quality, issued standard methods for ambient air quality monitoring and established a national environmental monitoring network to implement monitoring of ambient air quality. The first air pollution law went into effect in 1987. It has since been amended in 1995 and 2000 (World Bank, 2001). The 2000 amendment included several new mandates to enhance future air quality management, including the endorsement of emission fees and emission permits, both of which are potentially important regulatory instruments. Nevertheless, China still faces great challenges. Many of its cities have concentrations of sulphur dioxide and fine particulates that are amongst the world's highest (World Bank, 2001).

A total of nine pollutants comprise the Chinese air quality standards – sulphur dioxide, nitrogen dioxide, carbon monoxide, ozone, total suspended particulates, PM_{10}, lead, benzo(a)pyrene and fluorine. China has adopted three classes of ambient air quality standards: Class I are tourist, historic and conservation areas. Class II are residential urban and rural areas. Class III are industrial areas and heavy traffic areas.

The State Environmental Protection Administration is responsible for national ambient air quality monitoring in China. The National Environmental Monitoring Centre is an institution directly affiliated with the administration and provides technical support, supervision and service for environmental management, plays a role as a network technical and training centre for national environmental monitoring and provides professional management and guidance for the national monitoring system. It is responsible for collecting, verifying and managing the environmental monitoring information and statistical data (Fang *et al*., 2003). There are more than 2000 environmental monitoring stations directly under government control, including state, provincial, city and county-level stations. Measurement methods range from chemiluminescence for nitrogen dioxide, UV fluorescence for sulphur dioxide and UV photometric for ozone, to gravimetric for PM_{10}. A quality assurance and quality control programme exists to monitor the urban ambient air quality monitoring system.

Spatial modelling is one tool that has been used to assess compliance of certain cities with the air quality standards. One such study has taken place for the city of Shijiazhuang, an industrial city 275 kilometres southwest of Beijing and home to 1.5 million urban residents. Like most cities in China, Shijiazhuang relies overwhelmingly on coal to power its urban economy, and suffers serious environmental consequences as a result (Chaoyang *et al*., 2002).

The analytical tool used in this study was the Urban Branching Atmospheric Trajectory (UrBAT) model (Calori and Carmichael, 1999), a three-dimensional multi-layered Lagrangian model capable of estimating ambient concentrations at urban scale. The model is a modified version of the Atmospheric Transportation and Deposition (ATMOS) model (Heffter, 1983; Arndt *et al*., 1998) developed as part of the Regional Air Pollution Information and Simulation for Asia (RAINS - Asia).

Meteorological fields, terrain features, population density and emission sources were all incorporated as inputs into the UrBAT/ATMOS model, to generate spatial patterns of pollution dispersion and population exposure. Results show that the costs of premature deaths and morbidity cases amount to more than 4 percent of GDP in Shijiazhuang for the year 2000, highlighting the significant health costs associated with air pollution in Chinese cities (Chaoyang *et al*., 2002).

The environmental challenge facing China is huge. During the 1990s, the government devoted substantial financial resources to environmental improvements and made major efforts to strengthen the regulatory environment. The tide of industrial air pollution was stemmed, due substantially to the government's efforts. To a large extent, however, these efforts were overwhelmed by the government's strikingly successful growth and development programme. To meet future challenges, the government needs to re-order its priorities and revise its overall development policy, so as to significantly improve the fit between development and environmental sustainability (World Bank, 2001). Market-based policy initiatives, such as coal price reform and emission levies, to adequately internalise the externality of the health costs associated with air pollutants is critical to support urban air quality management and improve population health (Chaoyang *et al*., 2002).

4.7 International standards

As PM_{10} has played such an important role in air quality management internationally, Table 4.1 provides a summary of selected existing international air quality standards for this pollutant. As the main contaminant of concern for the case-study Marsden Point airshed, a similar list for sulphur dioxide is shown in Table 4.2. Of the major jurisdictions, only the United States has introduced a standard for $PM_{2.5.}$ The reason for this is that traditionally monitoring of particles has focused on total suspended particulates and PM_{10}, so that epidemiological studies have been conducted with these size fractions. This situation will change as jurisdictions are now

monitoring $PM_{2.5}$ on a routine basis and the epidemiology is indicating that $PM_{2.5}$ has an important role in the adverse health effects associated with particles. As for PM_{10}, there appears to be a growing consensus that 50 $\mu g\ m^{-3}$ is an appropriate guideline/standard for the 24-hour averaging period, although the US have retained a 24-hour standard of 150 $\mu g\ m^{-3}$ (Denison *et al.,* 2000). Standards should be considered together with the corresponding monitoring protocols. For example, the US standards are monitored at peak locations, whereas Australian standards are to be met at monitoring sites away from peak sources.

As will be seen in Tables 4.1 and 4.2, standard values in New Zealand are similar to those of the listed international standards for both PM_{10} and SO_2. Both the United States and China, and in the case of SO_2 also Australia, however have higher (less strict) standard values. Regional Councils in New Zealand are required to monitor and report exceedences as part of the regulations, and strict rules for managing the limiting pollutant include no new resource consents (discharge licences) to be issued should a gazetted airshed not comply with the ambient standard by the implementation date of September 2013. This point makes the New Zealand standards very strict in comparison with other countries. Regional Councils have been required to develop mitigation policies to ensure avoidance of the 'no new consents' rule and to regularly assess the effectiveness of their policies in mitigating any exceedences via monitoring. The number of allowable exceedences per year for the limiting pollutant is also strict in New Zealand when compared to other countries. For example, the 24-hour PM_{10} standard value in the United Kingdom is exactly the same as that in New Zealand, but allows up to 35 exceedences over the course of a year compared to a solitary permitted exceedence in New Zealand. In the European Union, exceedences of the 1-hour SO_2 standard are permitted 24 times per year and only nine times in New Zealand. The key point from the above is that the New Zealand air quality standards are possibly the most direct and strictest in the world.

Table 4.1 International air quality standards for PM_{10} (sources: MfE, 2003a; http://www.eng.me.go.kr/docs/cyber/filedown.html?filename=Ambient%20Air%20Quality%20Monitoring%20in%20China2.ppt; http://www.epa.gov/air/criteria.html).

Country/authority	PM_{10} standard ($\mu g\ m^{-3}$)	Averaging period	Allowable exceedences per year
New Zealand	50	24-hour	1
Australia	50	24-hour	5
United Kingdom	40 50	Annual 24-hour	- 35
European Union	40 50	Annual 24-hour	- 35
United States of America	50 150	Annual 24-hour	- 1
China - Class II - residential urban and rural areas	100 150	Annual 24-hour	-

Table 4.2 International air quality standards for sulphur dioxide (sources: MfE, 2003a; http://www.eng.me.go.kr/docs/cyber/filedown.html?filename=Ambient%20Air%20Quality%20Monitoring%20in%20China2.ppt; http://www.epa.gov/air/criteria.html).

Country/authority	SO_2 standard ($\mu g\ m^{-3}$)	Averaging period	Allowable exceedences per year
New Zealand	350 570	1-hour 1-hour	9 Never
Australia	60 230 570	Annual 24-hour 1-hour	-
United Kingdom	125 350 266	24-hour 1-hour 15-min	3 24 35
European Union	125 350	24-hour 1-hour	4 24
United States of America	80 365	Annual 24-hour	- 1
China Class II - residential urban and rural areas	60 150 500	Annual 24-hour 1-hour	-

4.8 Influences on the designation of air quality management areas internationally compared with New Zealand

Internationally, emissions sources other than those influential in the setting of management areas in New Zealand have played a far greater part in the designation of air quality management areas. In New Zealand, local air quality management areas (LAMAs) have been influenced more by domestic heating, the surrounding topography and the corresponding meteorological conditions.

For example, traffic emission sources account for over 95% of the air quality management areas (AQMAs) designated in the United Kingdom, indicating the importance of transport and land-use planning policies for promoting improvements in local air quality (Woodfield *et al*., 2002c). Table 4.3 indicates the sources of air emissions contributing to the air quality objective exceedences predicted by 120 UK authorities who have declared an AQMA.

Table 4.3 Emission sources responsible for air quality objective exceedences in the UK (source: Woodfield *et al.,* 2002c).

Emission source(s)	% of UK authorities
Traffic [a, b]	74
Traffic mainly (minor contribution from industry) [a, b]	12
Traffic [a, b] and industry [b, c]	5
Industry only [b, c]	4
Traffic [a, b] and construction emission source [b]	1
Traffic [a, b] and domestic source [c]	1

[a] NO_2 objective(s) [b] PM_{10} objective(s) [c] SO_2 objective(s)

In China, the main sources of air pollution are fine particulate matter from coal combustion, such as soot, flying ashes and especially sulphate. Within the city area of Shijiazhuang, an industrial centre in north-east China with a population of more than 1.5 million, there are over 8100 coal-fired boilers and industrial kilns, among which 30 are large point sources with high stacks over 45 metres (Chaoyang *et al*., 2002). The emissions from such sources have played a prime role in shaping air pollution management in China. As can be seen in Figure 4.1, particulate concentrations for Shijiazhuang are on a scale rarely seen elsewhere.

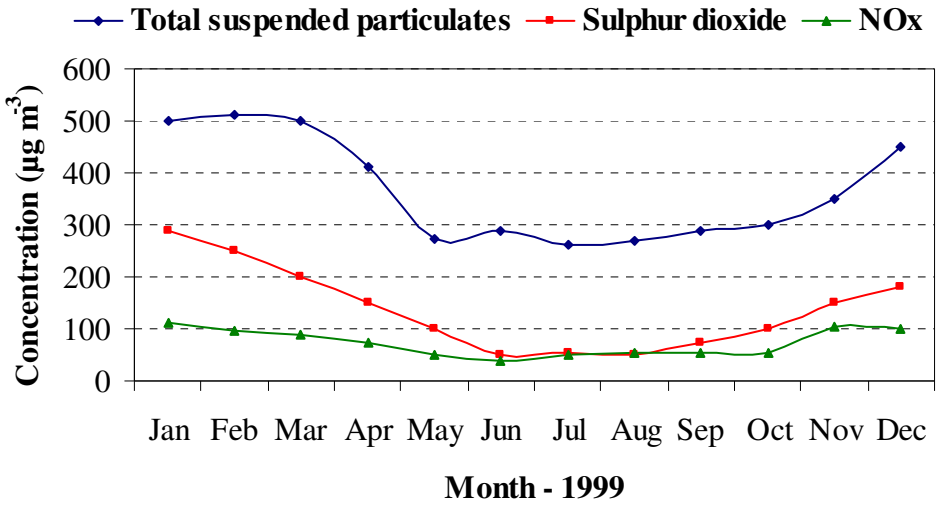

Figure 4.1 Observed monthly air quality indicators from monitoring data - Shijiazhuang, China (1999) (source: World Bank, 2001).

In New Zealand, home heating from solid fuel burning contributes greatly to New Zealand's pollution problems (see Figure 4.2), including highly populated areas such as Christchurch, during cold and calm periods in winter that restrict the dispersion of air pollutants. Other sources such as traffic emissions and industry play a smaller role in many parts of the country in contributing to overall air quality problems. The thesis case-study locality is, however, one area where industrial sources of sulphur dioxide have been the major influence in the setting of the Marsden Point airshed. Cities such as Auckland, with larger populations and access to home heating alternatives (e.g. natural gas), can experience air quality problems where vehicle emissions contribute to a greater degree.

A GIS based national PM_{10} emissions inventory has been established and used in the definition of New Zealand's local air management areas (LAMAs). The inventory includes domestic (wood and coal), industrial (point sources) and vehicle (exhaust pipe, brake and tyre wear, and dust re-suspension) emissions. In Masterton, a town of approximately 20,000 residents and lying on the flat river plain of the Wairarapa Valley in the south-east of the lower North Island of New Zealand, inventory data (Table 4.4) supports the above contention that home heating makes a major contribution to PM_{10} air quality problems in many towns of New Zealand. As a result, Masterton has been designated a Category 1 LAMA.

Table 4.4 New Zealand National PM_{10} Emissions Inventory Data - Masterton (source: Xie *et al.,* 2005).

Emission source(s)	% contribution
Domestic Heating	80
Vehicles	17
Industry	3

The contribution of motor vehicles or industrial sources to areas that experience episodes of poor air quality in New Zealand is indeed present, as in the cases of most designated airsheds in the Auckland region and the Marsden Point airshed in Northland. However, when compared to other countries where air quality standards and management have been introduced, it is clear that the emissions associated with domestic solid fuel fires have been influential to a greater degree in the designation of air quality management areas in New Zealand.

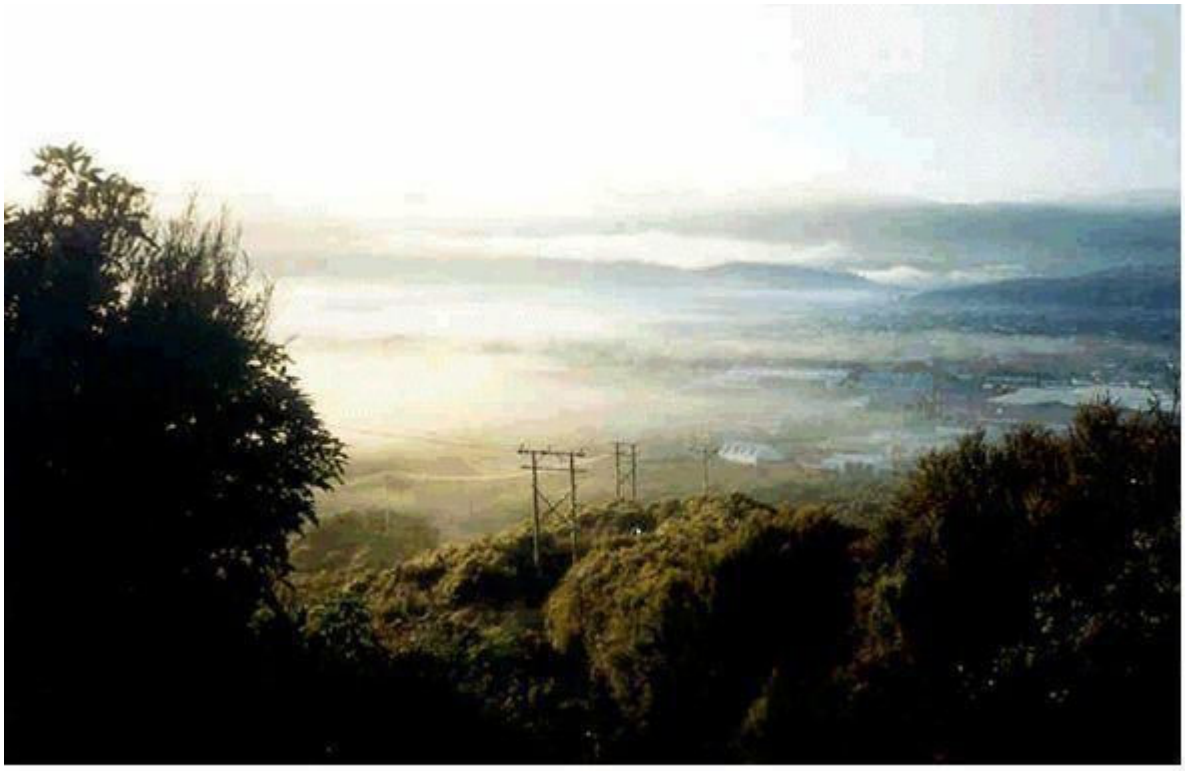

Figure 4.2 Emissions from domestic solid fuel burning produce smoke and haze lying in the Wainuiomata basin, near Wellington, during the winter of 2002 (source: Davy, 2003).

4.9 Summary

Methodologies used to develop air quality standards are often unique to a particular country and are often more complex and established than that in New Zealand, where standards have been established based purely on health and environmental considerations, rather than the political, cultural or social issues many other countries have been in addition forced to consider. The 'no new consents' rule, introduced as part of the NES, plus that of the small number of permitted exceedences of the standards in comparison to other countries makes the New Zealand NES for Ambient Air Quality amongst the most direct and rigorous in the world. The designation of air quality management areas in New Zealand has also been greatly influenced by emissions associated with domestic solid fuel fires when compared to many other countries where air quality management is enforced.

The focus of the thesis is now directed towards the modelling case-study, which commences in Chapter 5. The case study is an opportunity to undertake an independent analysis of the NES by applying atmospheric dispersion modelling to a selected air quality management area of a Regional Council in order to evaluate progress towards meeting the new standards by the target date of 1st September 2013. The specific case study considered by this research utilises The Air Pollution Model (TAPM), a self-contained PC-based model, consisting of coupled prognostic meteorological and air pollution concentration components, and which is applied to the only sulphur dioxide limited airshed in New Zealand following notification of the ambient air quality standards.

5. Case-study methodology

5.1 Introduction

This chapter commences the process of the modelling case-study by examining the airshed of interest, the Marsden Point airshed in Northland, and the meteorological conditions experienced within the airshed. Existing levels of the pollutant of interest to the modelling case-study (sulphur dioxide) are examined and analysed, as are industrial sources and shipping movements and their contribution to sulphur dioxide levels within the Marsden Point airshed. An analysis relating emissions from a major source within the airshed to monitored concentrations is carried out, and a review of the NES regulations as they apply to discharges of sulphur dioxide within an airshed and the consequences of non-compliance with the standards is also looked at. Finally, the model of choice for the case-study is introduced - TAPM. Inputs used in the model are listed and explained, as are the modelled scenarios and model configuration used for the two-day simulation period.

As previously mentioned in Chapter 1, despite PM_{10} being the driving force behind the NES, this thesis case-study concentrates on the only sulphur dioxide limited airshed in New Zealand as a result of the implementation of the NES. It is worth reiterating briefly the reasons:

- why this particular airshed has been chosen;
- why the particular contaminant has been selected, and
- why the simulation period is only two days.

The first two points can be explained as follows: The Northland Regional Council were interested from the outset, and most importantly possessed limited data that could be of use to the modelling project (unlike other previously contacted Regional Councils). The Council was also keen on the results that a modelling study of SO_2 within the only sulphur dioxide limited NES airshed in the country would provide. The third point can be explained firstly by the harsh reality of the vast amount of computing time required by TAPM to carry out a modelling run. It was discovered that carrying out long-term high-resolution simulations with multiple point sources is a computationally demanding exercise, and although far from ideal, it was considered appropriate for the purposes of this case-study to concentrate on the main contaminant of concern within the airshed for a limited time period when monitoring data was made available for comparison with the modelling results, highlighting the second reason as to the short simulation period, that is one-hour monitored values within the airshed were difficult to secure,

but two days (6th and 7th June 2005) were eventually made available. The short simulation period is undoubtedly a major limitation of the case-study project, but due to the above mentioned reasons, the modelling case-study proceeded.

However, initially we shall look at reasons as to why a modelling tool has been used to assess the implementation of the NES, and how the modelling process can help New Zealand Regional Councils achieve their NES objectives.

5.2 Why model?

Air quality modelling is a standard tool in addressing air quality issues and is accepted as being a component of any effective air quality management scheme. For the NES, this tool can be used to endorse a particular area as being one that may be more prevalent to pollution within an airshed, and therefore aid in establishing the correct location of compliance monitoring stations as stipulated by the NES. In addition to being a useful tool for assisting with site selection for NES compliance monitoring, dispersion modelling can also be used by regional authorities as a tool in assessing the effects of pollution mitigation options and to validate emission reduction strategies for NES compliance (i.e. straight and curved line paths). The modelling process can also be assigned to the selection or reassessment of Local Air Quality Management areas. Dispersion modelling is also a good instrument to validate monitoring records and provide confidence in both measurements and modelling results. As the process of determining straight/curved line paths and NES airsheds has been an activity of research in New Zealand over recent years, the reasons that modelling has been carried out for this thesis case-study are:

- to assess which sources and what mixture of sources (as scenarios) have the highest contributions to overall sulphur dioxide levels within the Marsden Point airshed;
- to validate modelling results with actual measurements within the Marsden Point airshed and consequently;
- to assess the location of present day and proposed sulphur dioxide monitoring locations, an important consideration to satisfy NES monitoring requirements, and
- to draw attention to any occurrence of NES breaches in order to assess progress towards meeting the sulphur dioxide standard.

5.3 The case study

In this thesis, atmospheric dispersion modelling (the conversion of emissions to concentrations) has been undertaken in order to provide an independent assessment of the application of the Ministry for the Environment's initiative regarding sulphur dioxide (SO_2) to a local government selected air quality management area - the Marsden Point airshed, Northland.

Pollutant dispersion modelling attempts to simulate the transport, deposition, dispersion and chemical reactions that occur in the atmosphere to estimate pollutant concentrations at a downwind receptor. This is a complex task that relies on choosing the most appropriate model and on obtaining realistic and reliable input data on emissions, meteorology and discharge characteristics that affect the modelling process (NIWA, 2004). Modelling is an important tool for determining the contribution of specific sources to the overall airshed and is therefore very important in control strategy development. It can also provide a means to determine the potential impact of a new, proposed source that has not yet been built. Models are therefore an important air quality management tool. However, they do not purport to provide precise answers, and results must be interpreted in this light (NIWA, 2004).

Following correspondence with several New Zealand Regional Councils, it was decided to utilise data supplied by the Northland Regional Council. Northland, shown in Figure 5.1, is New Zealand's northernmost region. It is bounded to the east by the Tasman Sea, to the west by the Pacific Ocean and to the south by the Auckland region. This peninsula shaped region has an approximate length of 250 kilometres and at its widest point is 80 kilometres. Geographically it covers 1,394,100 ha or 5.1 percent of New Zealand's land area. This land is predominantly hill country with flats restricted to river valleys and coastal areas. Of this area, farming utilises 45.5 percent and forestry 11.5 percent (MfE, 2003b).

Northland is the least urbanised region in New Zealand, with only slightly more than half the population living in urban areas (Statistics New Zealand, 1998). The region had 143,400 residents in 1997/98 or 3.7% of the national population (MfE, 2003b). Between 2001 and 2006 the population grew by 6%. Half of the population lived in the Whangarei district, 38% lived in the Far North district and 12% in the Kaipara district. Northland has a relatively large Maori population (29% in 2006), larger than the national average (14% in 2006) and a small proportion of Northlanders are migrants. In 2006 13% of Northland's population was born overseas, compared with 22% nationally. Across each of the three Northland districts there is a higher proportion of people aged under 15 compared with national figures, a lower than average

proportion of people aged 15 to 39 and a higher than average proportion of older residents (DOL, 2007).

Northland is home to New Zealand's only oil refinery. Marsden Point oil refinery is located near the mouth of the Whangarei Harbour (see Figure 5.1). Slightly less than half of the refinery's crude intake comes from the Taranaki region with the remainder imported predominantly from the Middle East, in particular Saudi Arabia and the United Arab Emirates (MfE, 2003b). Within the refinery, various processes are carried out which produce premium and regular motor gasoline, automotive and marine diesel, aviation and lighting kerosene, fuel oils and bitumens. Sulphur is recovered as an unwanted by-product and is sold as feedstock to the fertiliser industry. Carbon dioxide is recovered by a third-party for use in the beverage industry. Closely associated with the refinery is the Marsden A thermal power station which pipes heavy oil from the refinery for electricity production. Marsden A has a 240 megawatt capacity (MfE, 2003b). Marsden A last operated as a full generating unit in 1992 and has since been operated as a synchronous condenser providing stability to the electricity supply in the upper North Island of New Zealand. Synchronous condenser mode of operation is where the Unit 2 generator at Marsden A is connected to the national grid. This is an important part of the voltage support as it 'conditions' the power, reducing the losses to the end user. This role for Marsden A is expected to continue until at least 2010 (Salmon *et al*., 2005). In 2005, Mighty River Power Limited was granted approval for the mothballed Marsden B Power Station to operate as a coal-fired electricity generating station. Marsden B was built between 1975 and 1979 but was never commissioned. It was designed to run on oil, but the oil crisis of the late 1970s, combined with the discovery of the Maui gas field off Taranaki, led the Government to decide to put the plant into long-term storage. Regular maintenance has been undertaken over the past 30 years to enable the plant to be used in the future. Marsden A Power Station, situated adjacent to Marsden B, was built at the same time and generated electricity for a number of years (Salmon *et al*., 2005).

5.4 The airshed

In most cases, NES airsheds represent areas where it is known, or likely known, that the fine particle ambient standard is exceeded. The exception to this is the Marsden Point airshed, Northland which is based on sulphur dioxide (MfE, 2005). As the only SO_2 limited airshed in New Zealand, Marsden Point presented an interesting and unique challenge to this research.

The Marsden Point airshed presently contains several industrial point source emitters and in addition, the Whangarei District Plan and associated plan variation of the Marsden Point/Ruakaka area, has made provision for a significant increase in the area available for residential dwelling and for additional heavy industry. The contaminants identified as being critical in the Marsden Point area are sulphur dioxide (SO_2), particulate matter (PM_{10}) and nitrogen dioxide (NO_2) (NRC, 2005).

The airshed area incorporates a number of elevated terrain features located on Bream Head Peninsula. These features are important both because of the potential for high pollutant concentrations to occur on them, and for the effects they have on local meteorological conditions. Both land and sea breeze circulation (Section 5.5.4) and coastal fumigation phenomena (Section 5.5.6) are features of the area (NRC, 2005). Significant terrain features include hills to the north of Whangarei Harbour, namely Mt. Manaia, Mt. Aubrey and Mt. Lion, which range in height from 210m to 470m. Hills to the west and south-west (Ruakaka Forest) range in height from 200m to 260m. Figure 5.1 shows the Northland region and its location within New Zealand, plus a topographic map of the case study area for this research - the Marsden Point airshed (boundary outlined and shaded), located south-east of Whangarei. Whangarei Airport is located within the neighbouring Whangarei airshed.

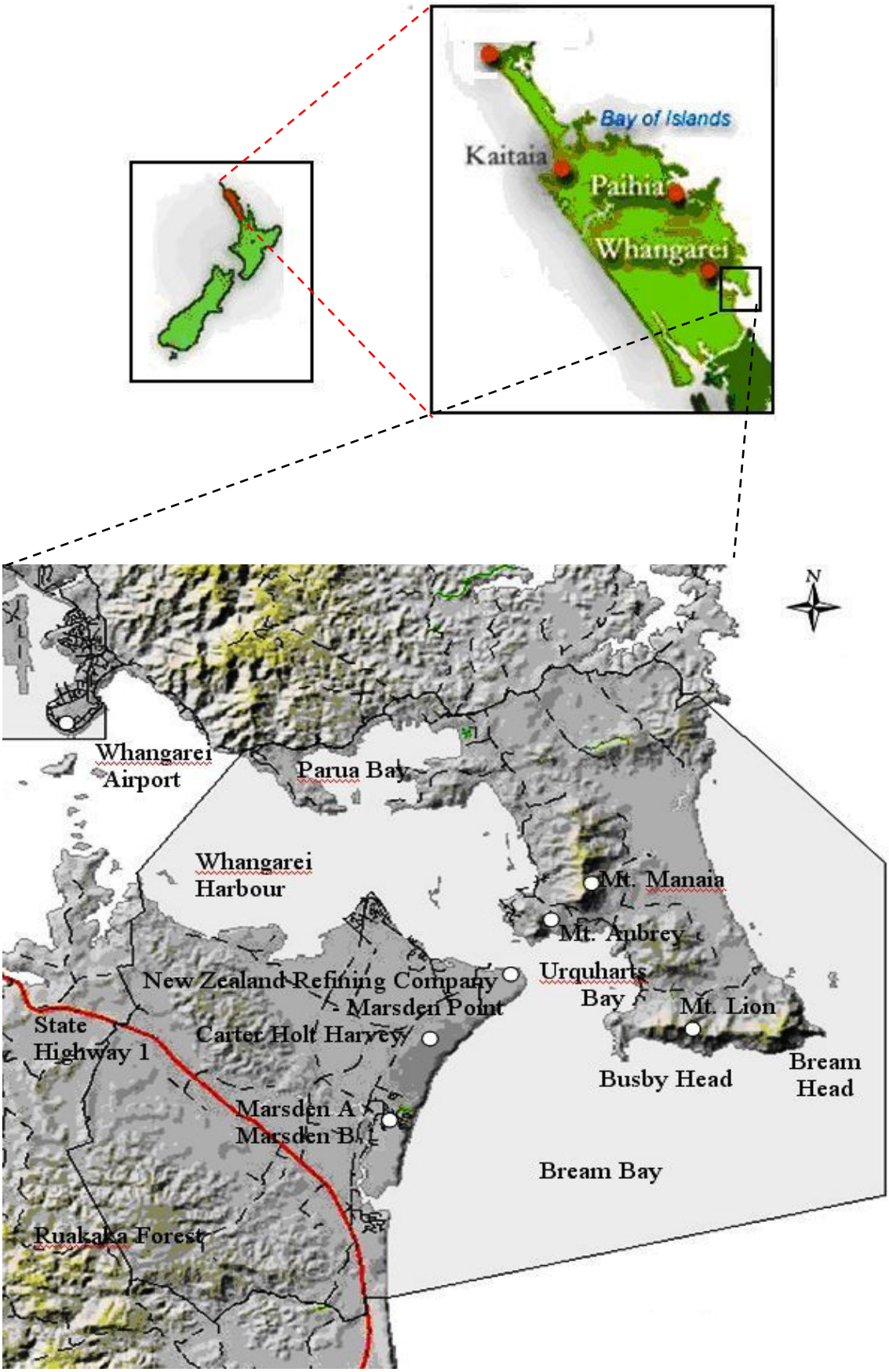

Figure 5.1 **Northland and the Marsden Point airshed - outlined and shaded (image source: Northland Regional Council). Marsden Point lies at 35° 49' 60"S latitude and 174° 30' 0"E longitude (NZ Map Grid 6595267, 2646166). Whangarei Airport is located within the Whangarei airshed.**

5.5 Meteorological conditions of the airshed

5.5.1 Measured wind speed and direction

Initially, wind conditions experienced at two meteorological stations are included to provide an indication of relative influences at each of the stations and the resultant effect of these influences on recorded wind information within the Marsden Point airshed. The prevailing surface winds in the airshed area predominantly blow from the west at the Marsden A meteorological station. The highest wind speeds however (> 4 m s^{-1}) blow from the north-east to the south-east for approximately 10% of the time (NIWA, 2004). The frequency distribution of occurrences of winds for each direction sector and for each wind class (wind rose) for the Marsden A meteorological station from November 1995 to March 2000 is shown in Figure 5.2. Figure 5.3 shows the wind class frequency distribution as a percentage for the same station and time period. In contrast, Figure 5.4 shows the frequency distribution of occurrences of winds for each direction sector and for each wind class (wind rose) for the Marsden Point meteorological station for the year 2001, highlighting the influences of the elevated terrain on the northern side of the harbour (which can cause eddies) and also showing the influence of on-shore sea breezes which are much less apparent at the Marsden A site and resulting in a predominantly easterly flow. The proximity of other objects such as buildings, stacks and oil tankers can influence both the wind direction and speed at this station. Figure 5.5 shows the wind class frequency distribution as a percentage for the same station and year, and also shows higher wind speeds are recorded at this site when compared to the Marsden A meteorological station.

Additionally, Figures 5.6 and 5.7 offer another example of different wind conditions in the area. Although outside the Marsden Point airshed and approximately 14 kilometres north-west of Marsden Point, the Whangarei Airport meteorological station, unlike Marsden A and Marsden Point stations, conforms to World Meteorological Organisation guidelines for station installation. Figure 5.6 shows the frequency distribution of occurrences of winds for each direction sector and for each wind class (wind rose) for the Whangarei Airport meteorological station for the years 2003 to 2006. Figure 5.7 shows the wind class frequency distribution as a percentage for the same station and time period.

Wind speed and direction obviously have a great bearing on where the highest ground-level concentrations of contaminants will result. Effects only occur downwind of the discharge. Highest concentrations occur when the wind speed is less than 2 m s^{-1} (or 7.2 km hr^{-1} - just

enough to blow paper along the ground) (Fisher & Heydenrych, 2005). As will be seen in Figures 5.3 and 5.5, these light winds are relatively common in the Marsden A monitoring area, but less common at the Marsden Point met station. When wind speeds are greater (up to 4 – 5 m s^{-1} or 15 km hr^{-1}), discharges can be carried further downwind, but dispersion starts to dilute the effects (Fisher & Heydenrych, 2005). Wind speeds at this level are seen more often at the Marsden Point meteorological station, occurring 30% of the time (see Figure 5.5). The Whangarei Airport meteorological station reports a higher percentage of calm periods (wind speeds < 0.5 m s^{-1}), with a northerly flow dominating but with substantial periods of winds from the north-west, west and south-west (see Figure 5.6) for the three-year monitoring period.

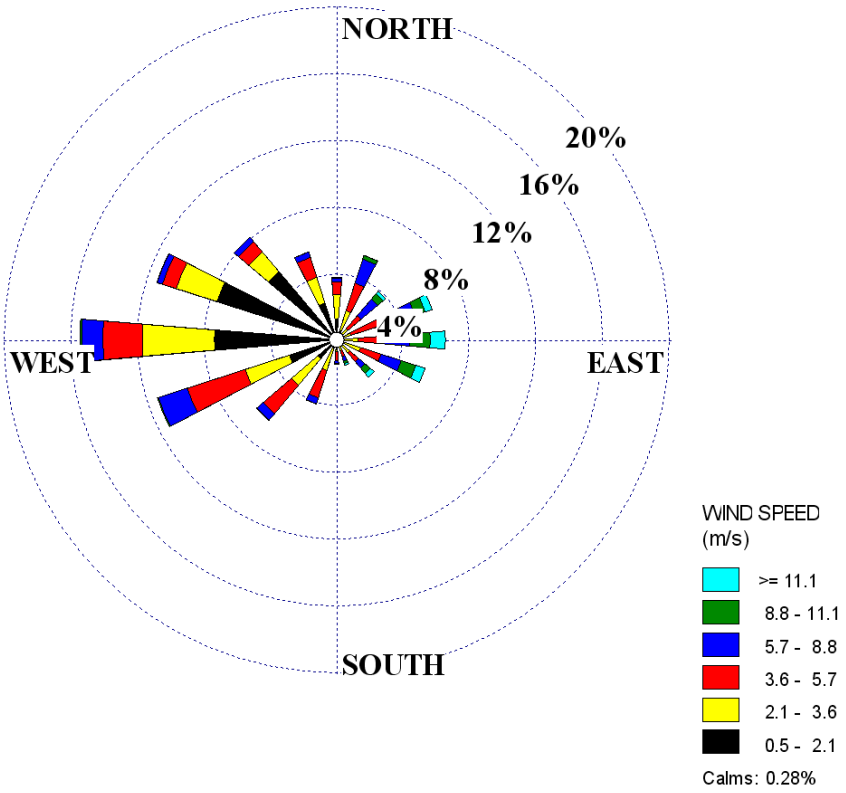

Figure 5.2 **Wind rose: Marsden A meteorological station, November 1995 - March 2000, showing the frequency of winds from given directions and in a range of speed classes.**

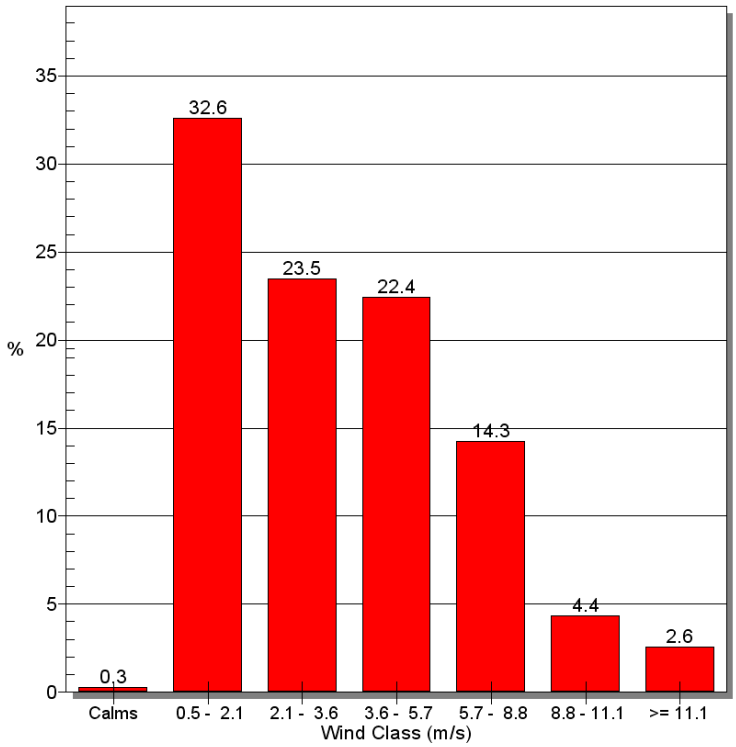

Figure 5.3 **Wind class frequency distribution: Marsden A meteorological station, November 1995 - March 2000. Average wind speed = 3.95 m s^{-1}.**

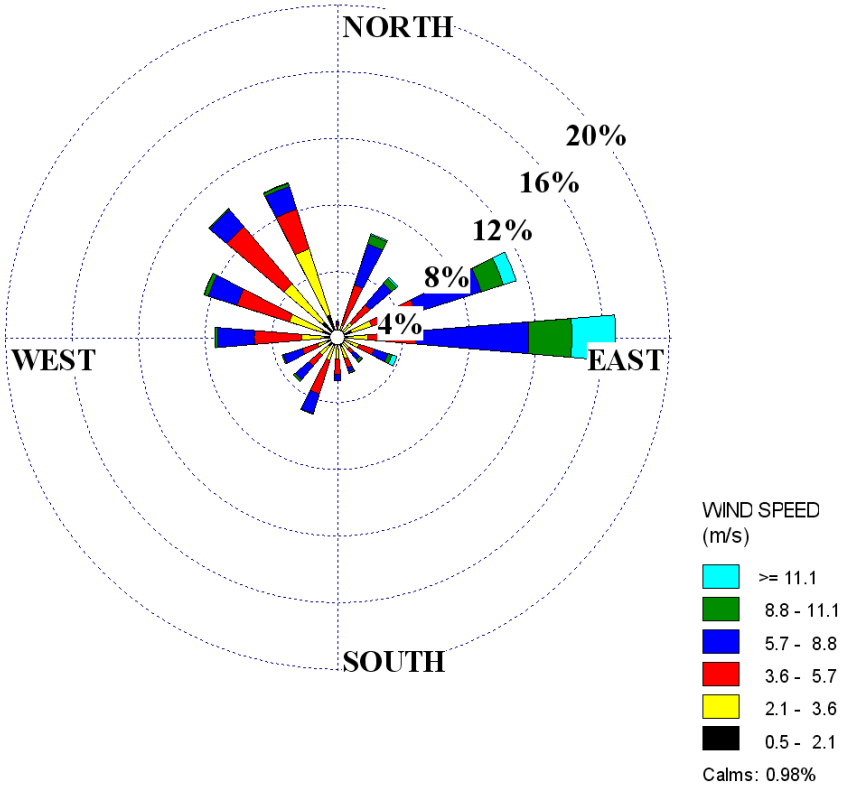

Figure 5.4 **Wind Rose: Marsden Point meteorological station - 2001, showing the frequency of winds from given directions and in a range of speed classes.**

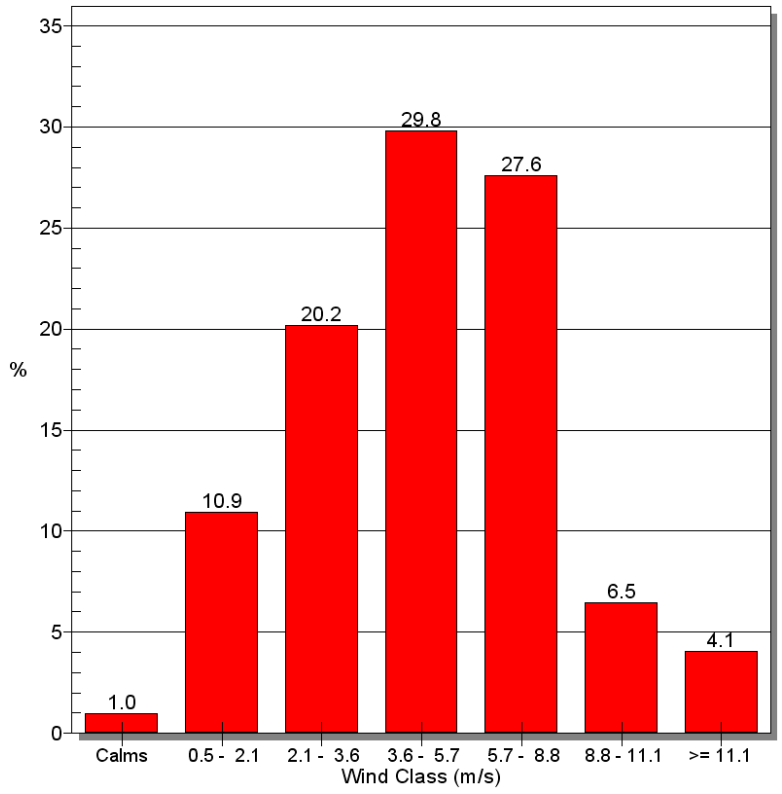

Figure 5.5 **Wind class frequency distribution: Marsden Point meteorological station - 2001. Average wind speed = 5.25 m s^{-1}.**

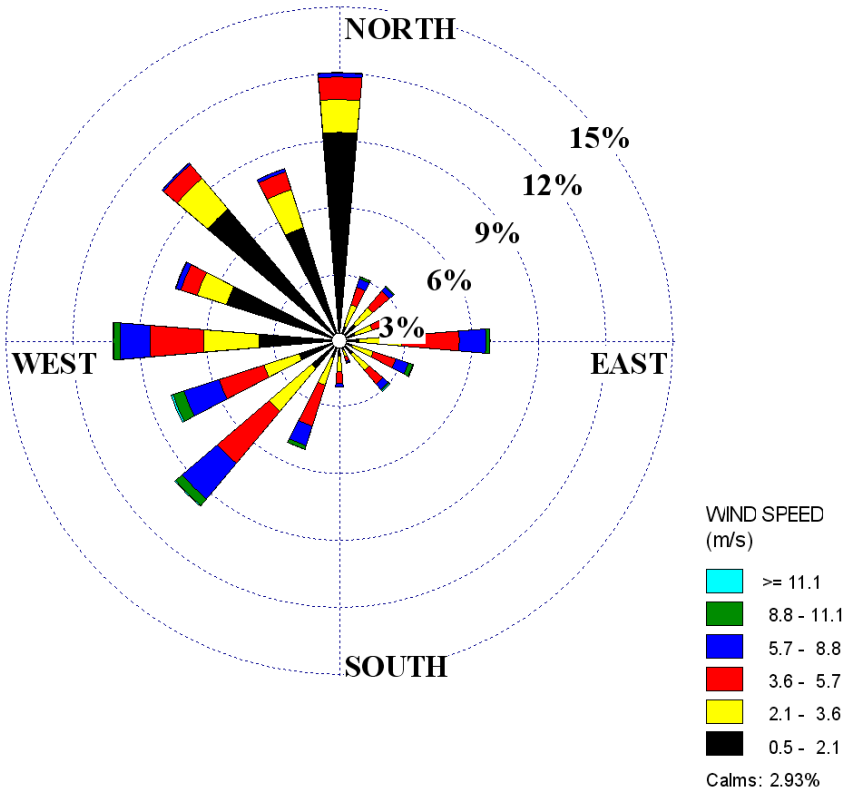

Figure 5.6 **Wind rose: Whangarei Airport meteorological station, 2003 - 2006, showing the frequency of winds from given directions and in a range of speed classes.**

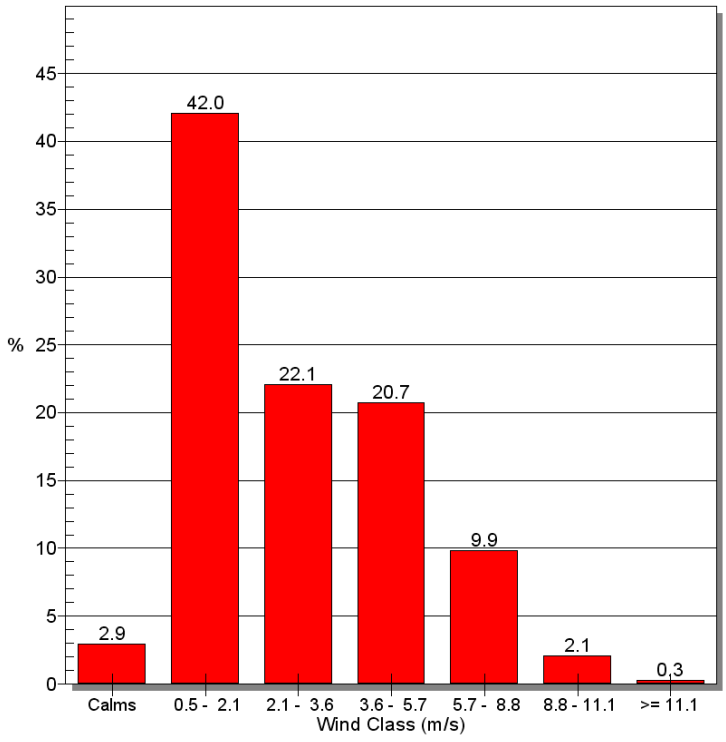

Figure 5.7 **Wind class frequency distribution: Whangarei Airport meteorological station, 2003 - 2006. Average wind speed = 3.11 m s^{-1}.**

The average wind speed at the Whangarei Airport meteorological station is less than both the Marsden A and Marsden Point sites, with a greater percentage of calm periods also occurring at this site. This site is considered by the Northland Regional Council to record conditions that are representative of the wider area and which are not unduly influenced by local topography, and is the major reason for utilising this meteorological sites' data later in the modelling case-study for comparison with model produced wind conditions of the area. Figures 5.8 and 5.9 show wind conditions recorded at the Whangarei Airport meteorological station for the case-study simulated period of 6th and 7th June 2005, showing a dominant yet mostly light to moderate south-westerly, but with a calm to light north-westerly also occurring for approximately 15% of the time.

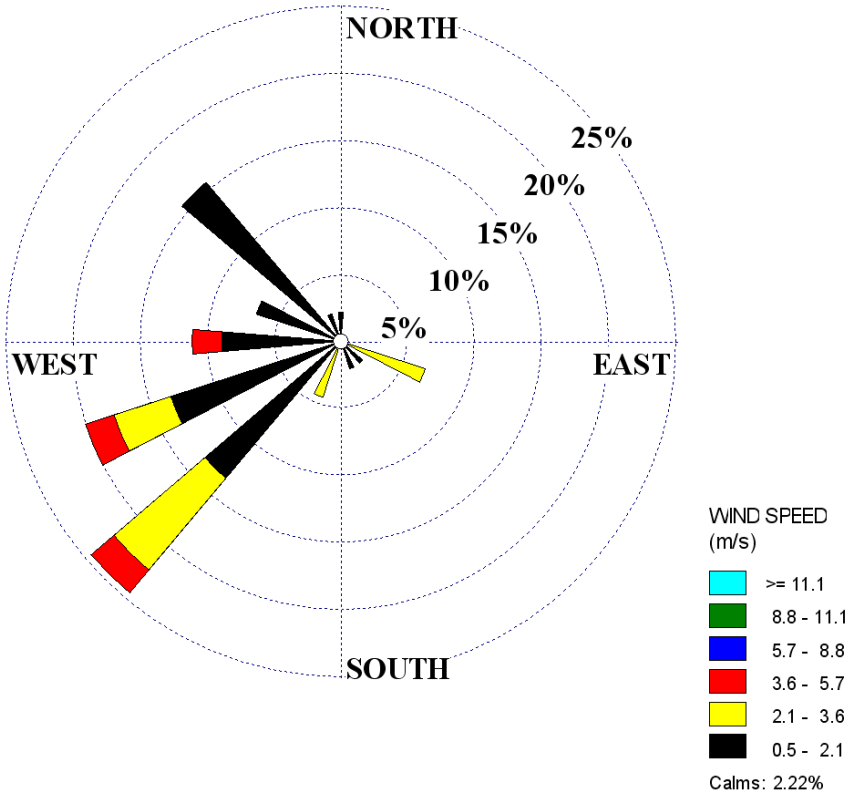

Figure 5.8 Wind rose: Whangarei Airport meteorological station for the case-study simulated period of 6th and 7th June 2005, showing the frequency of winds from given directions and in a range of speed classes.

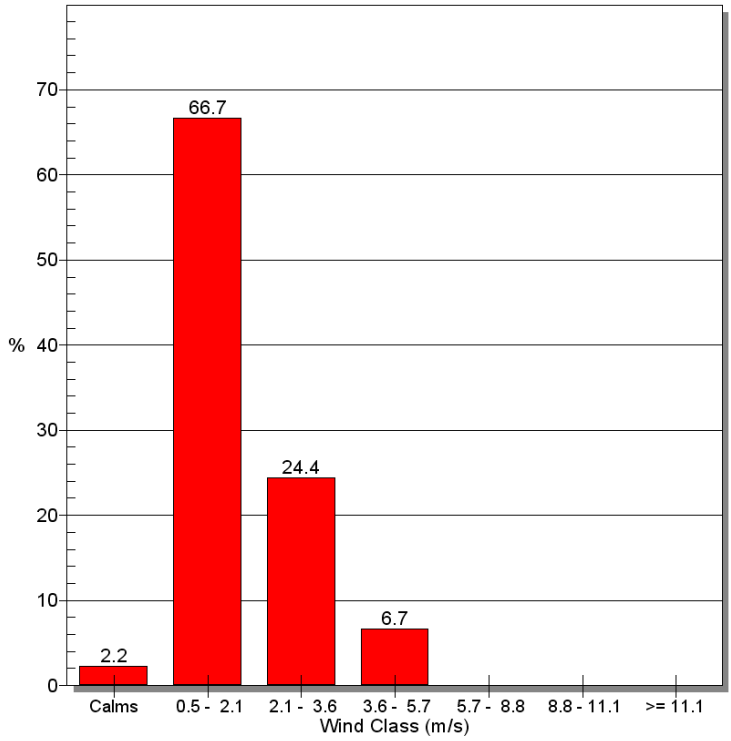

Figure 5.9 Wind class frequency distribution: Whangarei Airport meteorological station - 6th and 7th June 2005. Average wind speed = 2.00 m s-1.

5.5.2 Synoptic situation

Figure 5.10 shows the average 1000 hectoPascals geopotential height (height of a pressure surface above mean sea-level) in metres for 6th and 7th June 2005. This data has been obtained from the NCEP/NCAR (National Centers for Environmental Prediction/ National Center for Atmospheric Research) Reanalysis Project, a data set describing the state of the Earth's atmosphere from 1948 to the present-day and freely available online. On the 6th and 7th June 2005 a high pressure centre was situated to the west of New Zealand, thereby a relatively strong south-westerly affected most of the country including the region of interest to the modelling case-study. This is consistent with wind direction measured at the Whangarei Airport meteorological station for the same time period (see Figure 5.8).

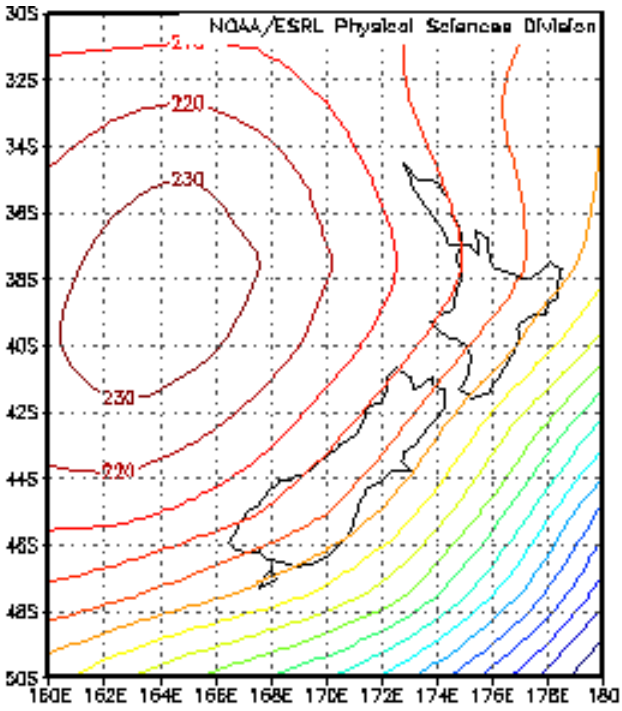

Figure 5.10 NCEP/NCAR Reanalysis of average 1000hPa geopotential height for June 6th and 7th 2005, showing New Zealand and the region of interest situated to the right of a south-westerly producing high pressure centre (source: NOAA-CIRES Climate Diagnostics Center, Colorado - http://www.cdc.noaa.gov/).

5.5.3 Mountain and valley winds

Mountain-valley winds are a result of diurnal warming and cooling of the terrain surface. Daytime heating in the upper part of a valley results in a mass of warm buoyant air which rises, drawing air up the valley system as a valley wind. At night, cold air moves down the valley creating a mountain wind. Both the day and night-time components of the system have a counterflow aloft to complete the circulation (Sturman & Tapper, 1996), which can net and/or recirculate air contaminants in the mountain-valley system. A schematic representation of mountain and valley winds is provided in Figure 5.11.

As previously mentioned, the Marsden Point airshed incorporates a number of elevated terrain features located on Bream Head Peninsula, amongst others. Mt. Manaia, Mt. Aubrey and Mt. Lion are all important for the effects they have on local meteorological conditions. Looking east and north-east respectively across the harbour from the New Zealand Refining Company site, Figures 5.12 and 5.13 clearly show how these hills have the potential to have an effect on local meteorological conditions. Residential buildings are also visible along the shoreline. These types of winds generated from the above mentioned features of Bream Head Peninsula will have an

influence on recorded conditions at the Marsden Point meteorological station, whilst the elevated terrain of the Ruakaka Forest area will have an impact on wind conditions recorded at the Marsden A meteorological site.

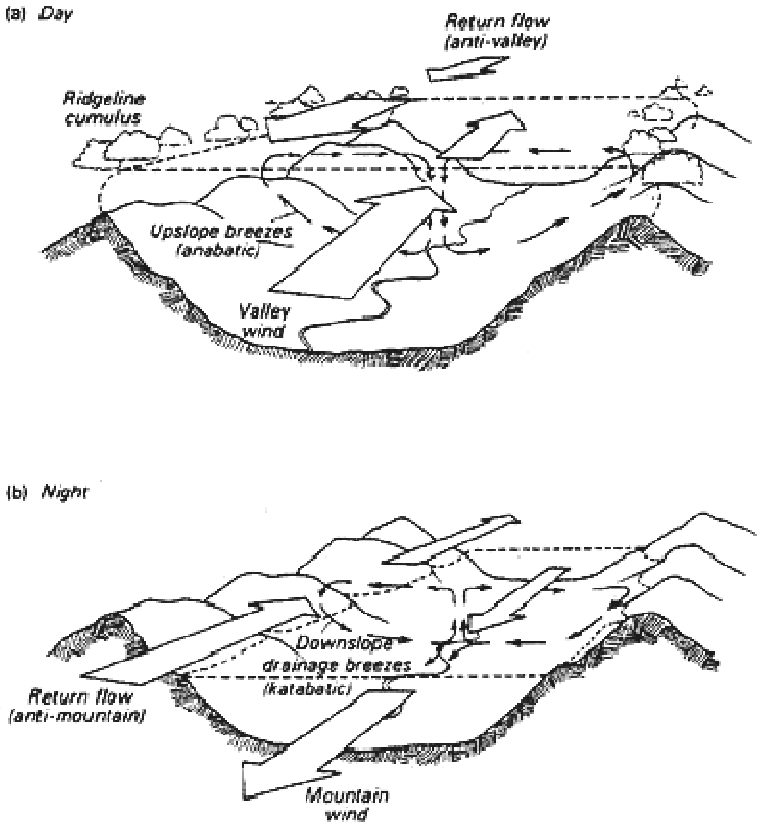

Figure 5.11 Mountain-valley wind system: (a) By day slope winds are anabatic, and the valley wind fills the valley and moves upstream with the anti-valley wind coming downstream. (b) At night the slope winds are katabatic and reinforce the mountain wind which flows downstream, with the anti-mountain wind flowing in the opposite direction above (source: Ahrens, 1994).

Figure 5.12 Looking east over the New Zealand Refining Company site to the hills on Bream Head Peninsula (source: http://www.TeAra.govt.nz/EarthSeaAndSky/MineralResources/OilAndGas/ en).

Figure 5.13 Looking north-east to the hills on Bream Head Peninsula (source: http://www.TeAra.govt.nz/EarthSeaAndSky/MineralResources/OilAndGas/en).

5.5.4 Land and sea breeze circulation

Localised wind flows can develop during daytime as the air over the land warms more quickly than the air over the sea. It rises, bringing in an onshore breeze, with a return flow aloft. At night the opposite occurs and a land breeze develops, flowing towards the sea under an area of subsidence. In Whangarei, sea breezes often occur on warm summer days. Sea and land breezes can both have significant effects on air quality over urban areas, as they re-circulate air currents that can return pollutants to an area from which they were released earlier in the day (Pendergast, 1984). On-shore sea breezes are more common at the Marsden Point meteorological site within the Marsden Point airshed than the Marsden A or Whangarei Airport sites (see Figure 5.4). A schematic representation of sea and land breezes is provided in Figure 5.14.

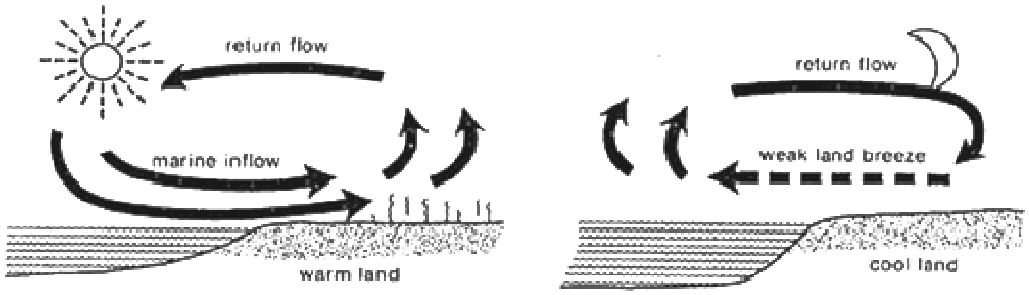

Figure 5.14 Sea breeze (l) and land breeze (r) (source: Pendergast, 1984).

5.5.5 Convection

Convection (the vertical movement of air generated by surface heating in the atmosphere) and seasonal differences also play active roles in determining ground level concentrations of pollutants at a particular place and time. During warm, calm conditions, vertical thermal currents can mix the plume down to the surface, even at distances of a few kilometres from the source. Seasonal differences, mainly due to the predominance of different weather types in each season, tend to produce lighter winds in winter. Spring and autumn tend to have stronger winds and summer has more convection. Generally, winter will produce higher pollutant concentrations due to the lighter winds which in turn fail to disperse contaminants.

5.5.6 Coastal fumigation

Plume fumigation can occur when an elevated onshore pollution plume intersects a growing thermal internal boundary layer contained within marine airflow coming onshore. For this particular study, the New Zealand Refining Company and the proposed Marsden B coal-fired power station are two such onshore pollution sources within the Marsden Point airshed. Convective mixing over land can rapidly bring elevated pollutants to the ground, causing local high ground-level concentrations which can persist for several hours and in the same location. A schematic representation of coastal fumigation is provided in Figure 5.15.

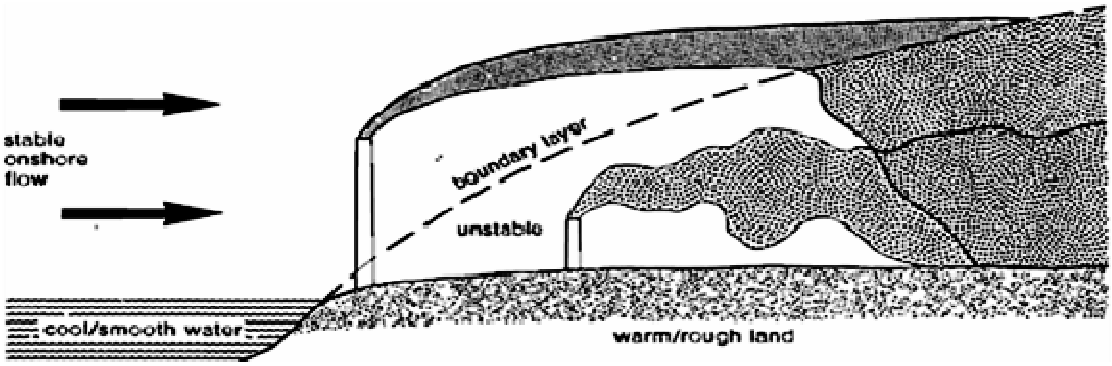

Figure 5.15 Coastal fumigation (source: Bluett *et al.*, 2004).

5.5.7 Rainfall and temperature

Rainfall and temperature data are available for Whangarei from a station located at Whangarei Airport (35.767°S, 174.367°E, 37m asl). This is a sub-tropical climate zone, with warm humid summers and mild winters. Typical summer daytime maximum air temperatures range from 22°C to 26°C, but seldom exceed 30°C. Winter daytime maximum air temperatures range from 12°C to 17°C. Annual sunshine hours average about 2000 in many areas. Winter usually has more rain and is the most unsettled time of year. In summer and autumn, storms of tropical origin may bring high winds and heavy rainfall from the east or north-east (NIWA, 2006b). Figure 5.16 shows average rainfall and temperature data for Whangarei for the years 1971 - 2000, including 14 years of complete data.

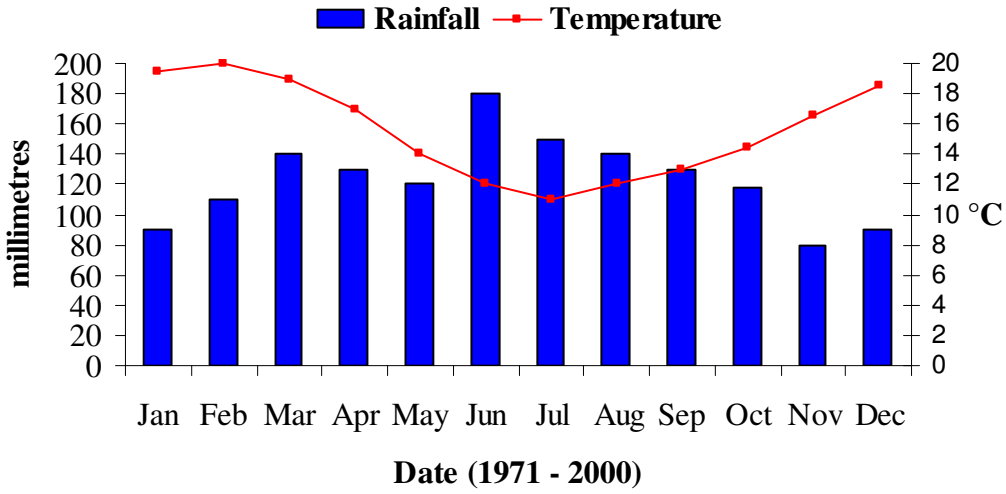

Figure 5.16 Average rainfall and temperature data for Whangarei (1971 - 2000) (source: NIWA, 2006b).

5.6 Existing sulphur dioxide levels

Sulphur dioxide is monitored in the Marsden Point area. The New Zealand Refining Company (NZRC) operates SO_2 monitoring sites at Little Munroe Bay on the Bream Head Peninsula, Whangarei Heads School and Urquhart's Bay. A fourth site was operated alongside the Takahiwai Rugby League clubrooms by Northland Regional Council between January 2000 and February 2001. The Takahiwai site was initially established by Electricity Corporation of New Zealand and SO_2 monitoring at the site commenced in May 1993. In 2000, the Northland Regional Council took over monitoring at the site (NIWA, 2004). Figure 5.17 shows the above-mentioned four monitoring locations plus the proposed SO_2 (and PM_{10}) monitoring station locations as part of NES requirements.

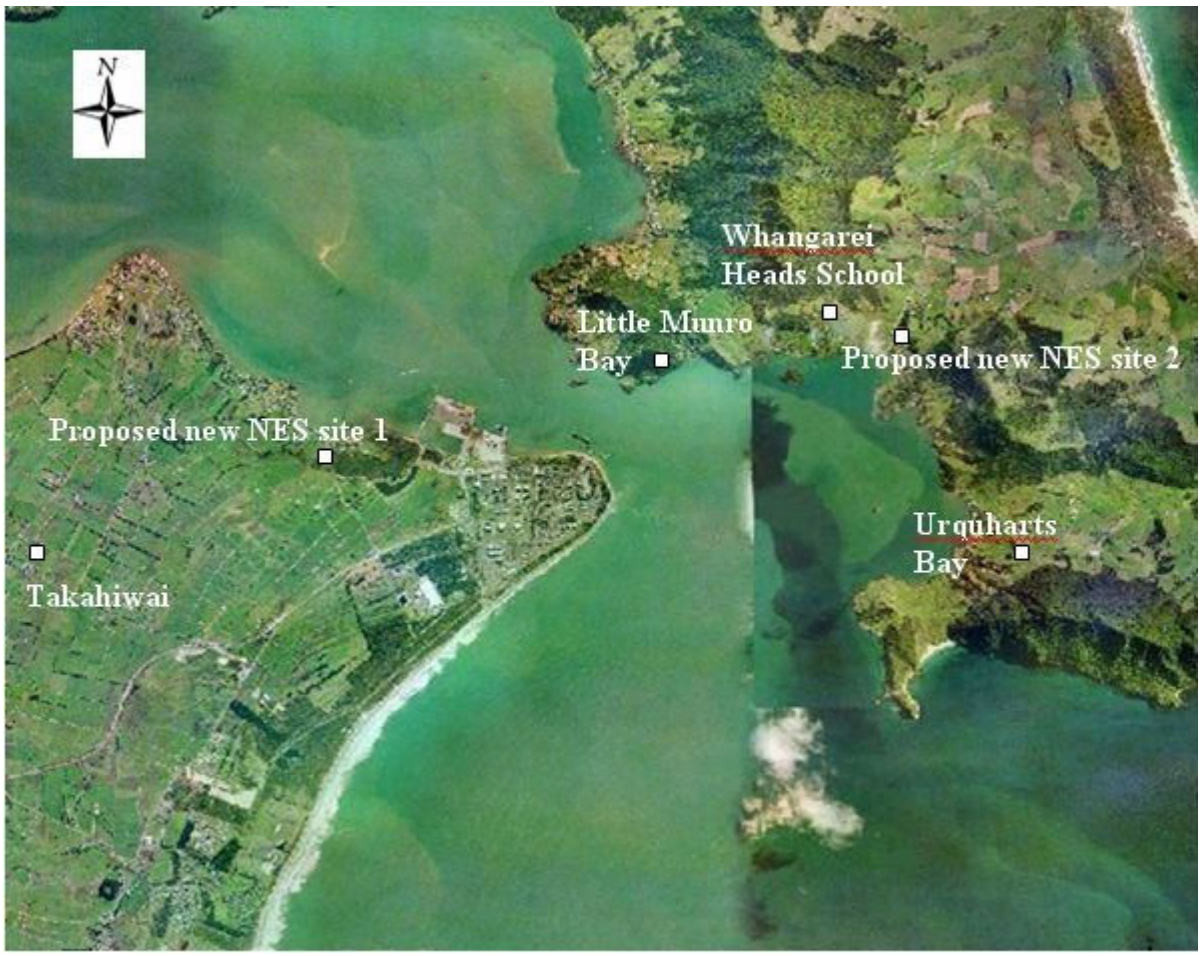

Figure 5.17 Locations of SO_2 monitoring stations in the Marsden Point airshed (aerial photograph courtesy of Northland Regional Council).

Figure 5.18 shows monthly average SO_2 concentrations derived from hourly readings and monitored between January 2000 and February 2001 at the Takahiwai Rugby League clubrooms by the Northland Regional Council. Figure 5.19 shows monthly maximum SO_2 values for the same site and time period. The New Zealand Refining Company completed alterations to their process resulting in lower levels of SO_2 emissions in 2000. This is reflected in the lower monitoring results of Figures 5.18 and 5.19 when compared to monitoring results of previous years. However, 'minor process upsets' have occurred since. Figure 5.20 shows one such 'upset' that occurred during 2005.

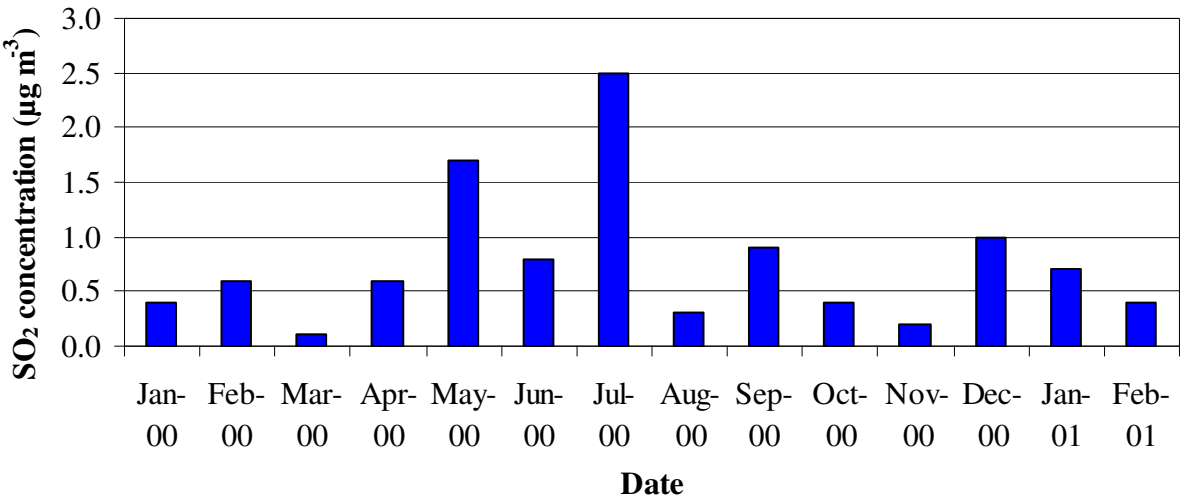

Figure 5.18 Monthly average SO_2 concentrations at the Takahiwai monitoring site, January 2000 - February 2001 (raw data supplied by Northland Regional Council).

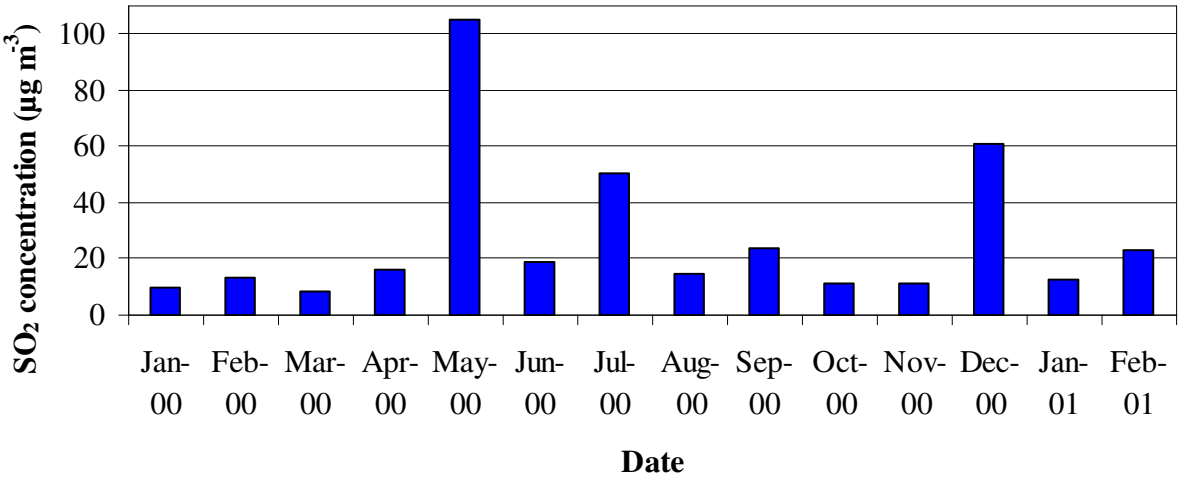

Figure 5.19 Monthly maximum SO_2 concentrations at theTakahiwai monitoring site, January 2000 - February 2001 (raw data supplied by Northland Regional Council).

Figure 5.20 'Minor process upset' at the New Zealand Refining Company - 2005 (photograph supplied by Northland Regional Council).

Figure 5.21 shows daily average sulphur dioxide concentrations as monitored between 1st January 2005 and 31st July 2006 at the Whangarei Heads School, Little Munro Bay and Urquharts Bay sampling sites. The highest impacts occur at the Whangarei Heads School site.

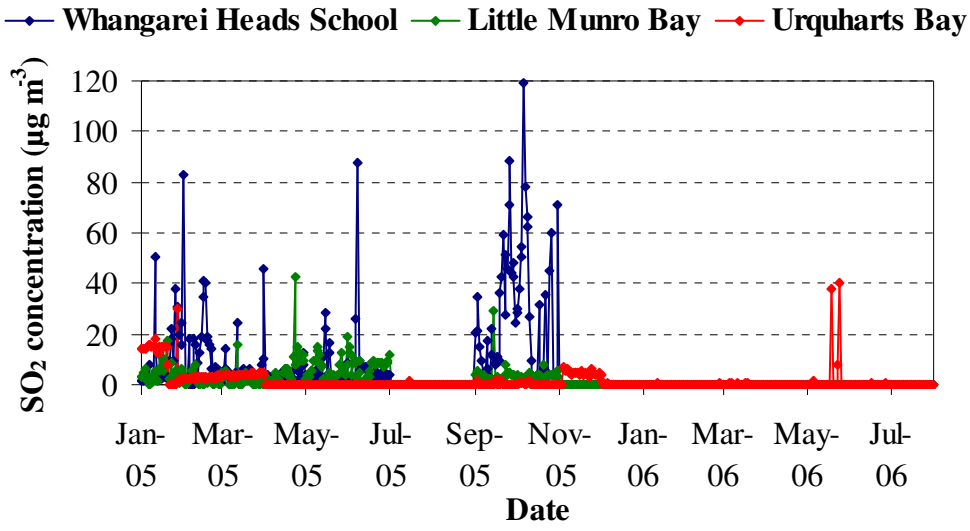

Figure 5.21 Marsden Point airshed daily average SO_2 monitoring results: January 2005 - July 2006 (raw data supplied by Northland Regional Council).

Figure 5.22 compares daily SO_2 emissions from NZRC with daily averaged monitored concentrations of SO_2 at Whangarei Heads School for the same time period, and highlights the influence and importance of meteorology on ground-level pollutant concentrations. As can be seen, the highest recorded concentration (119 µg m^{-3}) at this monitoring station occurred when 11 tonnes of SO_2 were emitted. On days when much larger amounts were emitted (e.g. 30.1 and 29.5 tonnes on 5th and 6th May 2006 respectively), recorded concentrations were barely above zero. This may highlight poor monitoring quality for the sampling period (there are also large gaps of missing data) or simply that the monitor was located up-wind of the source on these days, but the overall trend would indicate that the influence of meteorology is also important.

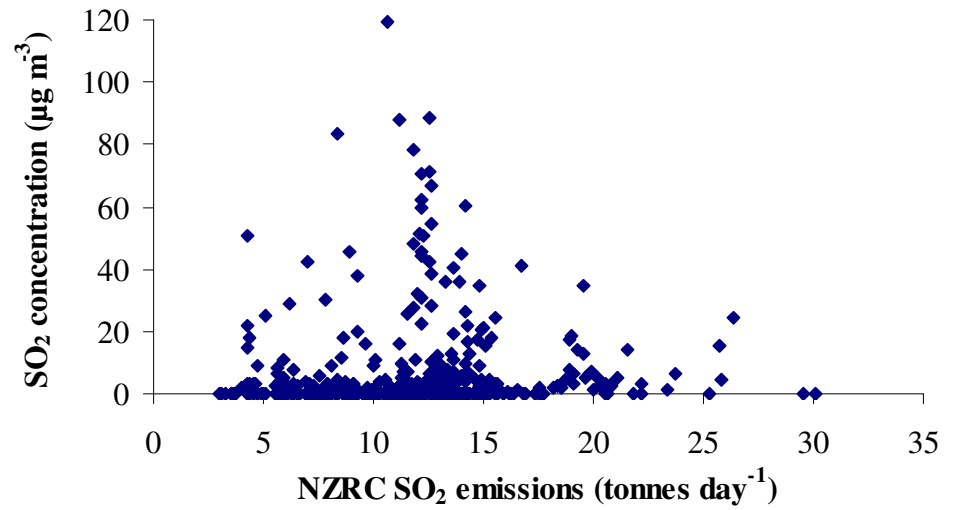

Figure 5.22 Daily NZRC emissions of SO_2 and daily averaged monitored concentrations of SO_2 at Whangarei Heads School: January 2005 - July 2006 (raw data supplied by Northland Regional Council).

To elaborate on SO_2 emissions and monitored concentrations in Figure 5.22, Figure 5.23 shows the frequency distribution of occurrences of winds for each direction sector and for each wind class (wind rose) for the Whangarei Airport meteorological station for the same time period of January 2005 to July 2006. Figure 5.24 shows the wind class frequency distribution as a percentage for the same station and time period. Low wind speeds ranging from a north-west to south-west direction dominate the monitoring period.

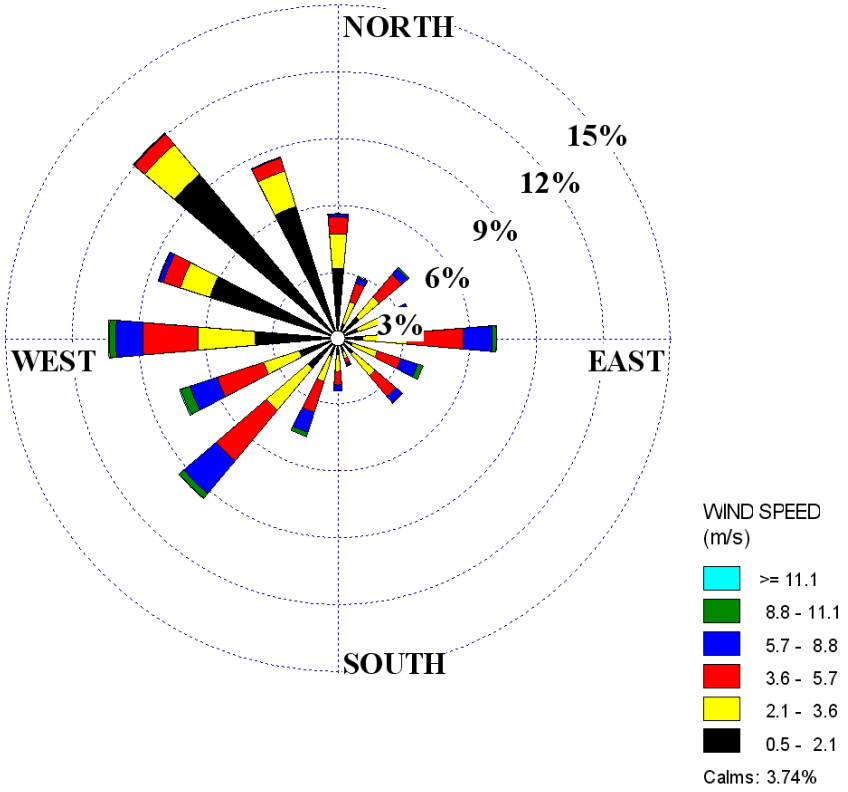

Figure 5.23 Wind Rose: Whangarei Airport meteorological station, January 2005 - July 2006, showing the frequency of winds from given directions and in a range of speed classes.

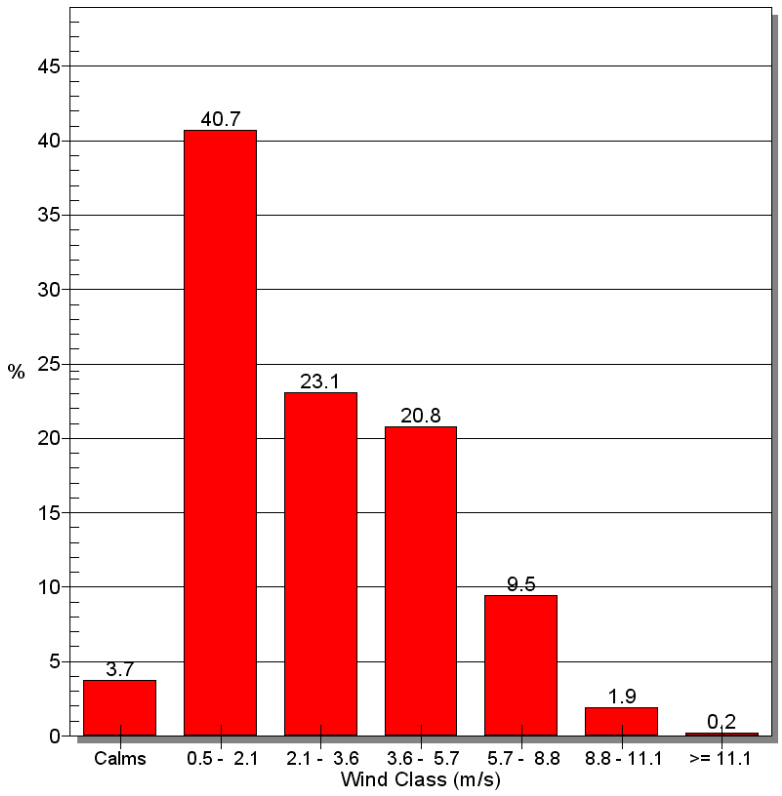

Figure 5.24 Wind class frequency distribution: Whangarei Airport meteorological station, January 2005 – July 2006. Average wind speed = 3.13 m s^{-1}.

To further expand and reinforce the influence of meteorology on ground-level pollutant concentrations, a 'pollution rose' has been constructed. This is equivalent to a wind rose, but where wind direction is correlated with SO_2 concentration rather than wind speed. Daily averaged monitored concentrations recorded at the Whangarei Heads School from January 2005 to July 2006 are shown in Figure 5.25, in combination with daily averaged monitored wind direction for the same time period from Whangarei Airport meteorological station.

The pollution rose shows a significant feature. The majority of SO_2 measurements recorded at the Whangarei Heads School site are when the wind is blowing from a north-west direction, further up Whangarei Harbour and possibly from Whangarei City itself. This reinforces the point first mentioned to describe Figure 5.22 when recorded SO_2 concentrations at Whangarei Heads School barely registered on days when large amounts of SO_2 were emitted from the New Zealand Refining Company, and suggesting potential sources of SO_2 at this monitoring site from outside the Marsden Point airshed. There are also measurements of SO_2 concentrations when the wind is blowing from the industrial and shipping areas within the Marsden Point airshed, but for the period January 2005 to July 2006, these sources do not contribute the same amount of SO_2 as those north-west of the monitoring site.

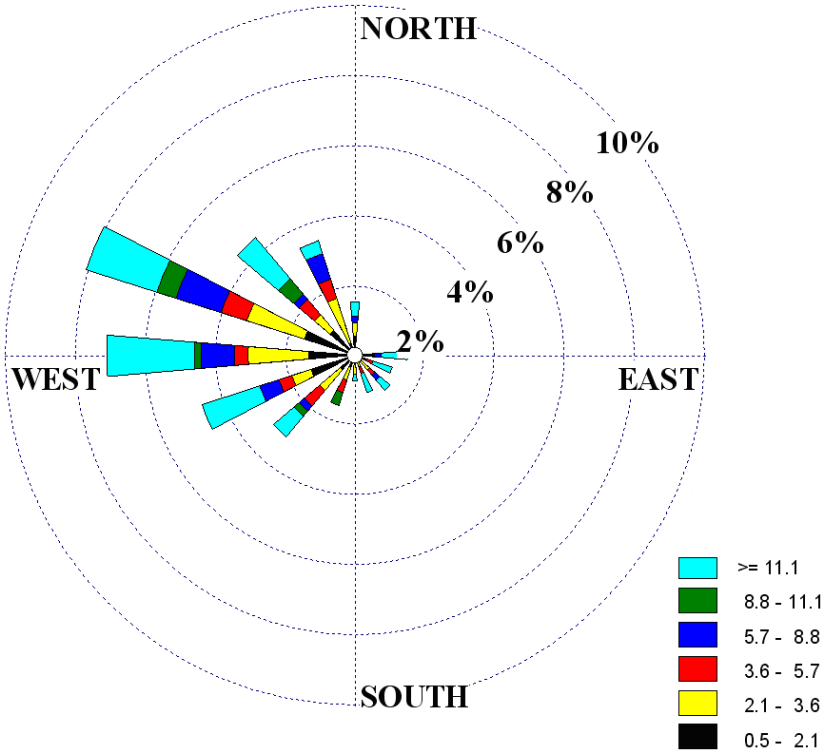

Figure 5.25 Pollution rose: daily averaged monitored SO_2 concentrations at Whangarei Heads School, January 2005 - July 2006 combined with daily averaged monitored wind direction for the same time period from Whangarei Airport meteorological station. Units for colour bar values are in µg m^{-3}.

5.7 Sensitivity of the receiving environment

Sensitivity to air quality impacts will vary with land use type. For example, land use including residential homes, hospitals, day-care centres, aged-care homes and schools will typically have greater sensitivity than a commercial or industrial setting.

Residential areas exist to the south and south-west of the Marsden A / Marsden B power station site. Bream Bay, an area frequented by recreational users lies to the east of this site. Further north lies the Marsden Point industrial area which is close to significant terrain features that include hills to the north and north-east of Whangarei Harbour, namely Mt. Manaia, Mt. Aubrey and Mt. Lion. South-west (prevailing) winds can carry industrial stack discharge plumes towards these hills. Under certain conditions, high contaminant concentrations can result on the side of the hills. The sensitivity of the hills is primarily related to vegetation effects rather than human health effects, as there are no residences or workplaces that will be affected by higher contaminant concentrations on these hill slopes. These effects have been the subject of consent

conditions and monitoring requirements in the past for emissions from the New Zealand Refining Company (NIWA, 2004).

Soil and vegetation monitoring carried out between 2002 and 2005 suggests that refinery emissions to air of sulphur do not appear to have had an adverse effect on vegetation sulphur concentrations at Mt. Manaia, Mt. Aubrey and Kauri Mountain (a control site). However, refinery air emissions of nitrous oxides may be responsible for increased nitrogen concentrations in vegetation at Mt. Aubrey, but not at Mt. Manaia. Soil nitrate concentrations increased between 2003 and 2005, while vegetation concentrations decreased (Bioresearches, 2005).

5.7.1 Residential areas

Residential properties and schools do exist on the lower reaches of the above mentioned hills (see Figures 5.12 and 5.13), some not too far beyond a good 'stones throw' across the harbour entrance from the Marsden Point Refinery site. These properties lie directly in the path of the prevailing south-westerly downwind from the refinery. Also, south and south-west of the proposed Marsden B coal-fired power station are residential properties that lie approximately 700m from the site stack (NIWA, 2004).

5.8 Cumulative effects

How emissions from different sources combine is of great importance when determining the overall impact of SO_2 emissions. At any point within the airshed, measured pollutant concentrations are the result of all sources that are upwind of the recorder. New Zealand Refining Company, Carter Holt Harvey and the proposed Marsden B coal-fired power station are the major sources of SO_2 emissions within the Marsden Point airshed. The New Zealand Refining Company are the major source of SO_2 emissions within this airshed from the common discharge point for B and C blocks. The proposed Marsden B stack also contributes significant emissions. Shipping movements may also give rise to emissions of sulphur dioxide, and where there are significant movements within a major port, there is the potential for the objectives to be exceeded (DEFRA, 2003). Calculated emission rates from shipping sources at two ports and a transit point at the mouth of Whangarei Harbour exceed the emission rates at the New Zealand Refining Company A Block, Carter Holt Harvey and Blacktop Asphalt industrial sites, and are therefore significant sources. Within the port industrial area, emissions from ships entering and leaving the Northport terminal will also contribute to SO_2 concentrations. In 1994, there were almost 300 coastal arrivals into the Port of Whangarei (NIWA, 2006a).

5.9 SO_2 emissions from shipping

The US Environmental Protection Agency has found that marine vessels can contribute to the deterioration of air quality in ports and along coastal areas (US EPA, 2003). Most marine vessels operate using diesel engines fuelled by either diesel (distillate) or residual (greater sulphur content) fuel. Diesel exhaust is made up of hundreds of components, both gases and particles. Some of the gaseous components include nitrogen compounds (e.g. nitrogen oxides), sulphur compounds, carbon dioxide and carbon monoxide (US EPA, 2002).

Sulphur dioxide emissions are directly related to the fuel sulphur level and are released from the exhaust system. Essentially all sulphur present is oxidised to form SO_2. Sulphuric acid (H_2SO_4) can also arise because of the production of sulphur trioxide (SO_3) and its subsequent reaction with water. Sulphuric acid reacts with basic substances to produce sulphates, which are fine particles that contribute to PM_{10} emissions.

The impacts of ship emissions can be of greater concern in some areas than in others, where local topography and microclimate can exacerbate the effect caused by pollutant emissions. As previously mentioned, the Marsden Point airshed area incorporates a number of elevated terrain features located on Bream Head Peninsula. These features are important both because of the potential for high pollutant concentrations to occur on them, and for the effects they have on local meteorological conditions.

5.9.1 Regulations

MARPOL 73 / 78 (MARine POLlution 1973 and 1978 - the International Convention for the Prevention of Pollution from Ships) is the international treaty regulating disposal of wastes generated by normal operation of shipping vessels. As of December 2001, New Zealand and 160 other countries were members. Regulation 14 of Annex VI of MARPOL 73 / 78 provides that the sulphur content of any fuel oil on board ships not exceed 4.5%, and requires that the worldwide average sulphur content of residual fuel oil used on board ships be monitored. A sulphur monitoring report (MEPC, 2002) found that in 80% of the samples reported, the sulphur content of fuel oil was between 2 and 4%. In 50% of the samples reported, sulphur content was shown to be between 2.5 and 3.5%. These statistics suggest that the actual sulphur content of most of the fuel oil currently used is significantly less than that allowed under Annex VI.

5.10 Shipping movements within the Marsden Point airshed

Figure 5.26 shows the number of commercial maritime vessels berthed at Marsden Port, the New Zealand Refining Company (NZRC) or transiting through the Whangarei Harbour entrance by month for the 12-month period commencing August 2005. The total number of ship berthings for the two ports plus those transiting through the harbour entrance (to likely berth further up the harbour at Port Whangarei or Golden Bay Cement) for the 12-month period was 556, with an average of 43 movements per month. The maximum monthly number of ship movements experienced during this time was 50, in July 2006. The least number of ship movements for the same period was 29, in February 2006. The NZRC had the greatest number of ship movements with 216. Table 5.1 summarises commercial ship movements for the years 2000 - 2005 for NZRC only. It would have been preferable to also have information relating to shipping movements for the two-day simulation period in June 2005, but this information was unfortunately not available according to the Northland Regional Habourmaster.

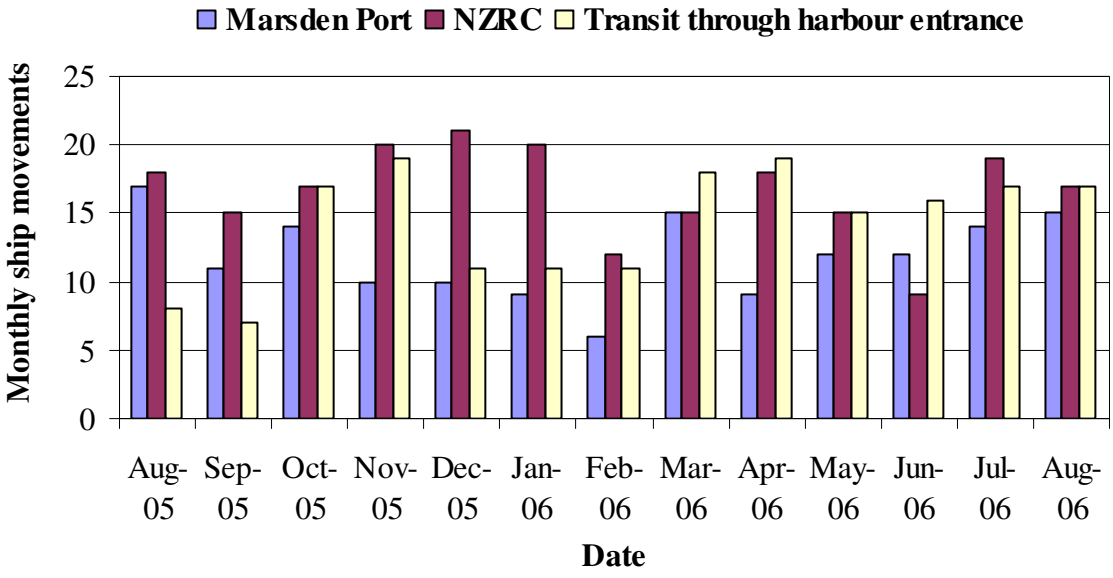

Figure 5.26 Number of commercial maritime vessels berthed at Marsden Port, NZRC Jetty 1 or transiting through Whangarei Harbour entrance by month: August 2005 - August 2006 (raw data supplied by Northland Regional Council).

Table 5.1 NZRC commercial ship movement summary: 2000 - 2005 (source: Northland Regional Council).

NZRC	2000	2001	2002	2003	2004	2005
Number of visits	161	183	182	194	191	216
Crude tankers	52	45	45	47	47	51
Coastal tankers	87	86	85	94	86	98
Blendstock imports	11	27	25	33	44	40
Exports	6	5	11	7	4	8
Bunker	5	20	16	13	10	19
Berth occupancy %	32	31	31	34	31	32

It should be noted that although there will be use of Whangarei Harbour and associated bays as venues for pleasure craft activities, this research study incorporates and analyses the emissions of SO_2 from commercial shipping movements at Marsden Point, the New Zealand Refining Company (NZRC) or transiting through the Whangarei Harbour entrance only.

5.10.1 Correlation between peaks in SO_2 concentrations and ship movements

Periods of high ship movements can equate to higher SO_2 concentrations being experienced within the airshed. It could also be argued that peaks in SO_2 concentrations may generally correspond with times when maximum ship movements are occurring. Although five years apart, average monthly concentrations of SO_2 recorded at the Takahiwai monitoring site for July 2000 (Figure 5.18) correspond favourably with the highest total number of commercial shipping movements (50) for July 2006. A direct comparison of ship movements and recorded concentrations at Takahiwai for July 2006 was not possible, as monitoring data for this site has been made available for the period January 2000 to February 2001 only. As July is also the middle of winter, meteorological conditions for this time of year may also contribute to higher monitored ground-level concentrations of SO_2.

5.11 NES and discharges of sulphur dioxide

Subclause 21 of the Resource Management (National Environmental Standards Relating to Certain Air Pollutants, Dioxins, and Other Toxics) Regulations 2004 states:

> Resource consents for discharge of sulphur dioxide:
> A consent authority must decline an application for resource consent to discharge sulphur dioxide into air if the discharge to be permitted by the resource consent is likely, at any time, to cause the concentration of sulphur dioxide in the airshed to breach its ambient air quality standard.

This requirement is quite clear in relating the discharge to the cause of the standard concentration being exceeded. This means that in areas with very low background SO_2 levels, Councils cannot grant consent to a large source of SO_2 that, on its own, would cause the concentration limit to be exceeded. Conversely, in areas of high background levels of SO_2, but below the standard concentration, (i.e. with existing industrial sources) it would not be permissible to grant consent to a small discharge of SO_2 if it pushed ambient levels in the air quality management area over the concentration limit (MfE, 2004a).

One of the fundamental deviations from the Ambient Air Quality Guidelines (1994) is the condition of 'allowable exceedences'. That is, the 1-hour SO_2 concentration is permitted to exceed the 350 $\mu g\ m^{-3}$ level, but for only 9 hours in any one year (0.1% of the time). The concentration is never to exceed 570 $\mu g\ m^{-3}$. This is to reflect the practical circumstances that some processes have unavoidable discharge events, and some peaks can be caused by rare weather conditions. Nevertheless, there is a maximum 'never to be exceeded' level that protects health (NIWA, 2004).

5.12 The Model

According to the Good Practice Guide for Atmospheric Dispersion Modelling (Bluett *et al*., 2004), one of the key elements of an effective dispersion modelling study is to choose an appropriate tool to match the scale of impact and complexity of a particular discharge. When choosing the most appropriate model the principal issues to consider are the complexity of dispersion (terrain and meteorology effects) and the potential scale and significance of effects, including the sensitivity of the receiving environment (human health versus amenity effects).

Air pollution models that can be used to predict pollution concentrations for periods of up to a year are generally semi-empirical/analytic approaches based on Gaussian plumes or puffs. These

models typically use either a simple surface-based meteorological file or a diagnostic wind field model based on available observations (Hurley, 2002). Essentially, a diagnostic model requires extensive observational data to accurately reproduce meteorological fields. The Air Pollution Model (TAPM) is different to these approaches in that it solves the fundamental fluid dynamics and scalar transport equations to predict meteorology and pollutant concentrations for a range of pollutants. It consists of coupled prognostic meteorological and air pollution concentration components, eliminating the need to have site specific meteorological observations. Instead, the model predicts the flows important to local scale air pollution, such as sea breezes and terrain-induced flows, against a background of larger-scale meteorology provided by synoptic analyses (Hurley, 2002), that is, prognostic models have forecasting capabilities. The only user-supplied data required for air pollution applications using a prognostic model are emission information, and indeed the absence and poor reliability of emission inventories in New Zealand appears to be the main limitation to progress in the application of prognostic models to air pollution dispersion (Zawar-Reza *et al*., 2005a).

Evaluations of TAPM against gaussian and puff models (Ausplume and Calpuff) by Hurley & Luhar (2005) and Hurley *et al*. (2005), using international tracer dispersion datasets, suggests that TAPM performs well against the other widely used models and that it has shown good performance across the four compared datasets, with consistently good prediction of the magnitude of extreme concentrations and the smallest number of errors of all models tested. Although stating that there is room for improvement, Adeeb (2004) found TAPM predicted meteorology and pollution with reasonable accuracy for a well-defined, high ground-level pollution period in Adelaide, South Australia. In a comparison study with another high resolution mesoscale model (MM5), Zawar-Reza *et al*. (2005b) found TAPM can predict meteorology and dispersion satisfactorily in the complex topographic setting of Christchurch, New Zealand.

5.13 Model inputs

Consideration is given to five industrial point sources within the Marsden Point airshed that contribute to overall SO_2 concentrations, plus that of SO_2 emissions from shipping activities within the airshed. Consent limits, as issued by the Northland Regional Council, have been used as inputs for the model for each of the industrial point sources. A full list of input parameters is contained in Appendix 1. With regard to shipping emissions, emission factors are used as presented by Lloyd's Register of Shipping (a maritime classification society), and contained within the Emission Estimation Technique Manual for Maritime Operations Version 1.1 (NPI, 2001). Activities covered in the manual apply to facilities primarily engaged in the operation of

ports (i.e. the loading and unloading of freight), ballasting, transit, and maintenance and general upkeep of ocean going and inland water vessels. Equations within the manual are used to estimate engine exhaust emissions of pollutants from main and auxiliary engines from port vessels. Equations and other information used to derive model inputs from ship emissions are contained within Appendix 2.

Factors influencing ship emission calculations include (input data for emissions calculations derived from information provided by Mr.Paul Baynham - Northland Regional Council, Mr. Ian Niblock - Northland Regional Habourmaster, and Mr. Mike Pryce - Wellington Regional Harbourmaster. Enquiries were also made to Northport Ltd., Maritime NZ and NZ National Maritime Museum):

- Average number of main engines per vessel = 1
- Average number of auxillary engines per vessel = 1
- Average main engine power rating (kW) = 18,500 for NZRC port; 15,000 for Marsden Port; 10,000 for vessels in transit; auxillary engine power rating (kW) = 600 for all.
- Average gross tonnage per vessel = > 50,000 for NZRC Jetty 1; 10,000 - 50,000 for Marsden Port and vessels in transit. This difference is important when deciphering the correction factor to be used in order to account for the sulphur content of the fuel.

Generally, vessels use main engines when entering and exiting Whangarei Harbour but switch to auxillary engines and use a better quality fuel when berthed. Table 5.2 details the characteristics of each of the eight (5 x industrial + 3 x shipping) point source emitters included in this study. Figure 5.27 shows the modelled point source locations within the Marsden Point airshed (shaded and outlined). The shaded outline in the top left corner of this diagram is part of the neighbouring Whangarei airshed.

Table 5.2 Marsden Point source data for SO_2 modelling case study (stack parameter inputs for model derived from info. provided by Mr. Paul Baynham - Northland Regional Council, Mr. Mike Pryce - Wellington Regional Harbourmaster and Concawe (1994)).

Source name	Source location coordinates (New Zealand Map Grid)	Stack height (m-agl)	Stack exit diameter (m)	Stack exit temp. (°C)	Stack exit velocity ($m\ s^{-1}$)	SO_2 emission rate ($g\ s^{-1}$)
NZRC A [a]	6594487 2645621	100	2.60	200	28	2.3
NZRC B & C	6594179 2645547	121	4.10	210	22	137
Marsden B	6594200 2644899	120 [b]	4.30	85.7	24.2	90 [c]
Carter Holt Harvey LVL plant	6593229 2644538	25	1.70	90	10	0.09
Blacktop Asphalts	6594476 2645633	10	1.0	170	12.8	2.2
Marsden Port	6595435 2644956	30	1.0	325	15	48.82
NZRC Jetty 1	6595036 2645986	30	1.0	325	15	60.25
Transit point [d]	6595234 2646241	30	1.0	325	15	33.07

[a] The NZRC (currently) incorporates three main sources of SO_2: A, B and C blocks. For practical purposes, B and C blocks utilise a common discharge point. C block produces the majority of SO_2 emissions.

[b] The Marsden B stack is at the time of writing yet to be installed. On 7th March 2007, Mighty River Power announced it had abandoned plans to recommission Marsden B coal-fired power station.

[c] Following flue gas desulphurisation.

[d] Transit point chosen as area off 'Home Point.' Vessels transiting through the harbour entrance can also berth further up the harbour at Port Whangarei or Golden Bay Cement. Golden Bay Cement is situated outside the Marsden Point airshed.

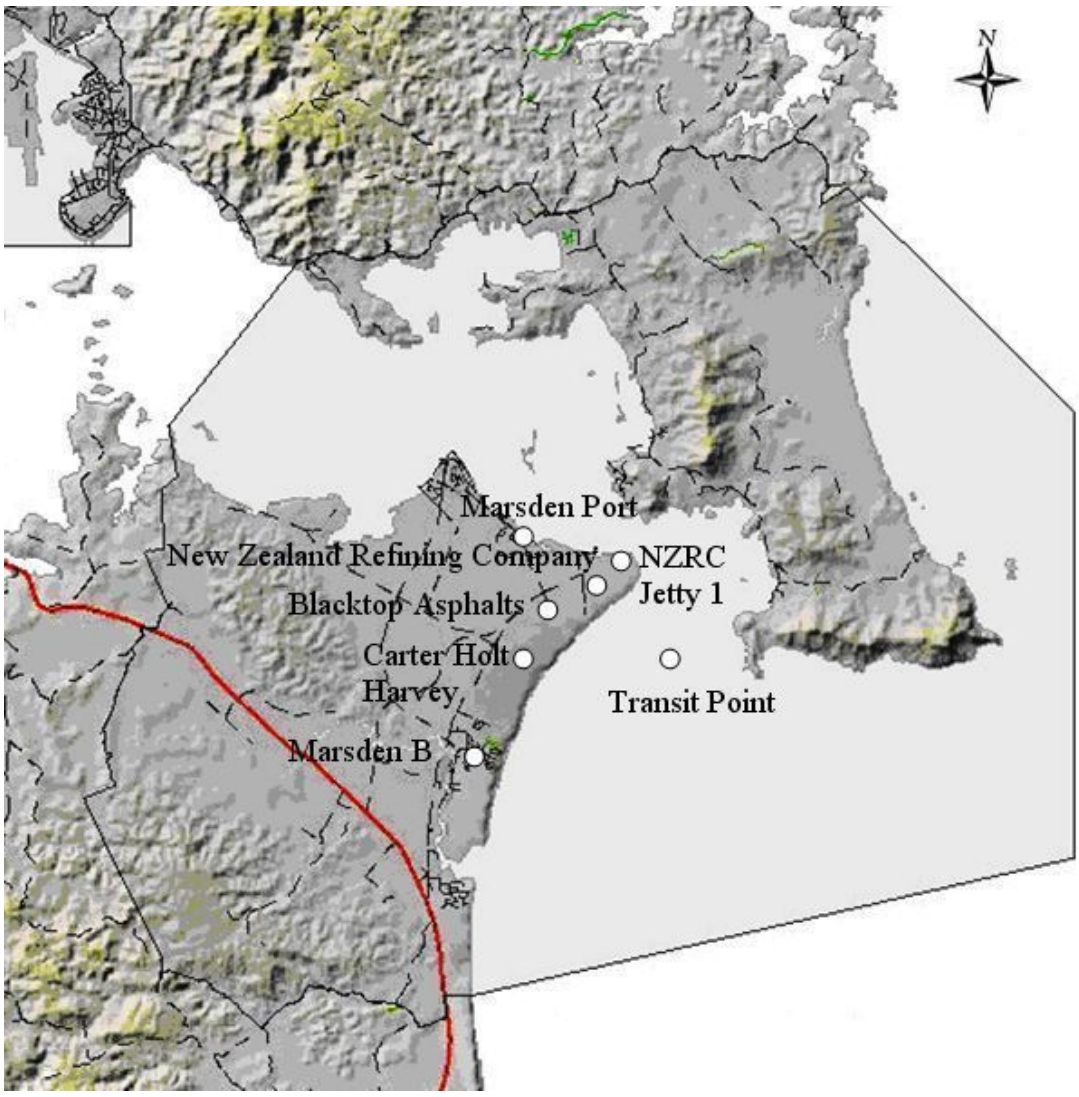

Figure 5.27 Modelled point source locations within the Marsden Point airshed (shaded and outlined) for the modelling case-study period of 6th and 7th June 2005. Shaded area in top left is part of Whangarei airshed (image source: Northland regional Council).

5.14 Modelled scenarios

One main question loomed large when determining exactly what different scenarios were to be modelled - which sources have the greatest impact on the airshed? From Table 5.2 (above) this can be seen to be both NZRC emissions and those associated with shipping movements. However, although the Marsden Point airshed can be quite busy over the course of any calendar year, shipping movements are transient and there will be times (albeit few) when little or no ship movements are occurring. On the other hand, the NZRC operates around the clock, 365 days per year, only stopping as required for routine maintenance. At any rate, the largest ship movement emissions are associated with activities at NZRC Jetty 1.

The modelled scenarios chosen for this case study were:

1. All sources
2. All sources minus Marsden B
3. NZRC only
4. NZRC + NZRC Jetty 1 only
5. Ship emissions only

The sources and modelled scenarios have been chosen in order to account for the major sources of sulphur dioxide within the Marsden Point airshed, not only to assess the relative contributions of the main industrial point sources but to also include and isolate the influence of shipping emissions to overall levels of sulphur dioxide.

5.15 Model configuration

Atmospheric dispersion modelling has been carried out using The Air Pollution Model (TAPM), version 3.0. TAPM consists of prognostic (forecasting) meteorology and air pollution modules that can be run for multiple nested domains. Meteorological simulations have been carried out with one mother grid of 19km horizontal resolution and four nested grids, with horizontal resolutions of 10km, 3km, 1km and 300m, each containing 51 nodes in the north-south and east-west directions and forty vertical grid levels; centred at 174 deg 29 min longitude and -35 deg 50 minute latitude. The corresponding pollution grid spacings simulate the exact same geographic extent but possess twice the resolution, each containing 102 nodes in the north-south and east-west directions.

The land-use classification was obtained from the TAPM dataset and the deep soil moisture setting was assigned the default value of 0.15 m^3 m^{-3} (i.e. volume of water per volume of soil). TAPM uses a synoptic scale meteorology dataset derived from LAPS (Limited Area Prediction System) or GASP (Global Analysis and Prediction) analysis data from the Bureau of Meteorology (BoM), Australia. Data assimilation was not performed and the dataset used in its' simplest mode. See Puri *et al*. (1998) or Hart (1998) for a description of LAPS or GASP respectively.

5.16 Summary

This chapter has introduced the modelling case-study for this thesis and reiterated the limitations associated with the case-study, particularly the short (2-day) simulation period. The meteorological conditions and sulphur dioxide levels within the Marsden Point airshed have been analysed and discussed. An analysis relating emissions to monitored concentrations has also been carried out, culminating in a 'pollution rose' suggesting potential sources of sulphur dioxide from outside the airshed. The model of choice for the case-study has also been introduced – TAPM. Inputs used in the model are listed and explained, as are the modelled scenarios and model configuration used for the two-day simulation period. Attention is now directed to the results of the modelling case-study in Chapter 6.

6. Results

6.1 Introduction

A reliable an accepted approach is to use the 99.9th percentile values for one-hour concentrations as the maximum ground-level concentrations likely to occur. This is the highest ground-level concentration at each receptor after the highest 0.1% of predictions has been discarded. The Good Practice Guide for Atmospheric Dispersion Modelling (Bluett *et al*., 2004) recommends providing an indication of the representativeness of the 99.9th percentile value ground-level concentration by also presenting other percentile values (e.g. maximum, 99.5th, 99.9th percentile values). This chapter will present results of the two-day modelling case-study of the Marsden Point airshed and also provide an initial analysis of the results. Individual sources such as the NZRC and shipping are looked at, and a comparison of modelled values, both SO_2 concentrations and meteorological conditions, is made with monitoring results. Modelled winds for the simulation period and their influence on resultant concentrations at a critical time (when monitoring records indicated high values of SO_2) on the Marsden Point hills are shown, as is an 'idealised run', where the influence and absence of synoptic meteorology in the Marsden Point airshed is assessed.

A summary of dispersion modelling results for SO_2 at a spatial resolution of 1km within the Marsden Point airshed for the two-day simulation period of 6th and 7th June 2005 is provided in Table 6.1. In line with recommendations included in The Good Practice Guide, maximum values are also presented. Two maximum ambient air quality concentration values for SO_2 are included within each row of results in Table 6.1. The SO_2 standard is 350 µg m^{-3} averaged over one hour and this will be achieved if 350 µg m^{-3} is not exceeded more than nine hours in a 12-month period (i.e. 99.9th percentile of 12-months of monitoring data), and none of these exceedences is above 570 µg m^{-3} (1-hr average).

The spatial distribution of ground-level concentrations of SO_2 from each of the modelled scenarios, both 99.9th percentile and maximum values, are shown in Figures 6.1 to 6.10 for the two-day simulation period of 6th and 7th June 2005. New Zealand Map Grid coordinates (metres) are used for the concentration contour maps. Plotted contour lines in red represent where the highest modelled concentrations occur. These contour lines fade to black as concentrations decrease. Contour lines are presented over a TAPM generated base map and with reference to the 51 x 51 km grid generated by the 1km spatial resolution. The small yellow squares on the base map represent the locations of the modelled point sources. Figure 6.11 shows plotted

concentration contours of 1-hour maximum SO_2 values from scenario one with locations of present-day and proposed NES SO_2 monitoring sites.

Highest modelled SO_2 concentrations were attributed to scenario one, with all sources used as inputs. Scenario two (all sources but excluding Marsden B) closely followed. Scenarios four (NZRC + NZRC Jetty 1) and five (ship emissions only) produced similar values to each other and were only marginally less than scenario two. By far the lowest concentrations derived from the model were from scenario three (NZRC only). All modelled emissions of SO_2 in the Marsden Point airshed for the two-day simulation period 6th and 7th June 2005 are within the corresponding National Environmental Standard (NES) for Ambient Air Quality.

It should again be noted that the simulation period for this case-study is only two-days. The dominant modelled wind direction for this period is from the south-west, but when looking at the wind direction as recorded at the most reliable measuring site for the wider area over a 3-year period (Whangarei Airport, see Figure 5.6) and considering the long-term dominance of wind conditions, the modelled pattern of conditions can only be expected to occur for approximately 10% of the time. Given the dominant wind directions recorded at the airport over a longer time frame, emissions from the Marsden Point area would be expected to occur to the south and south-east, however the Whangarei Airport recorded wind speed is low and conditions that dominate at the Marsden Point and Marsden A meteorological sites may take control of the plumes in this area. The on-shore breezes as recorded at the Marsden Point site are stronger and occur more frequently then the north to west arc of wind conditions recorded at the airport. It is truly a complex area for wind conditions and for assessing pollutant concentrations in the airshed. However, having stated the above, the modelled wind direction is supported by the recorded wind direction at Whangarei Airport (Figure 5.8) for the simulated dates of 6th and 7th June 2005.

Table 6.1 **Dispersion modelling results for SO_2 within the Marsden Point airshed for the two-day simulation period of 6th and 7th June 2005 at a spatial resolution of 1 km. The NES for SO_2 dictates that 99.9th percentile values (350 µg m^{-3}) must be met for all but nine hours each year. Maximum values (570 µg m^{-3}) must not be exceeded, that is, 100 percent of the time with no exceedances.**

Scenario	Time average	NES - SO_2 (µg m^{-3})	99.9th percentile value (µg m^{-3})	Maximum value (µg m^{-3})
1. All sources	1-hour	350 570	85 -	- 173
2. All sources excluding Marsden B	1-hour	350 570	83 -	- 172
3. NZRC only	1-hour	350 570	3 -	- 55
4. NZRC + NZRC Jetty 1 only	1-hour	350 570	76 -	- 150
5. Ship emissions only	1-hour	350 570	78 -	- 135

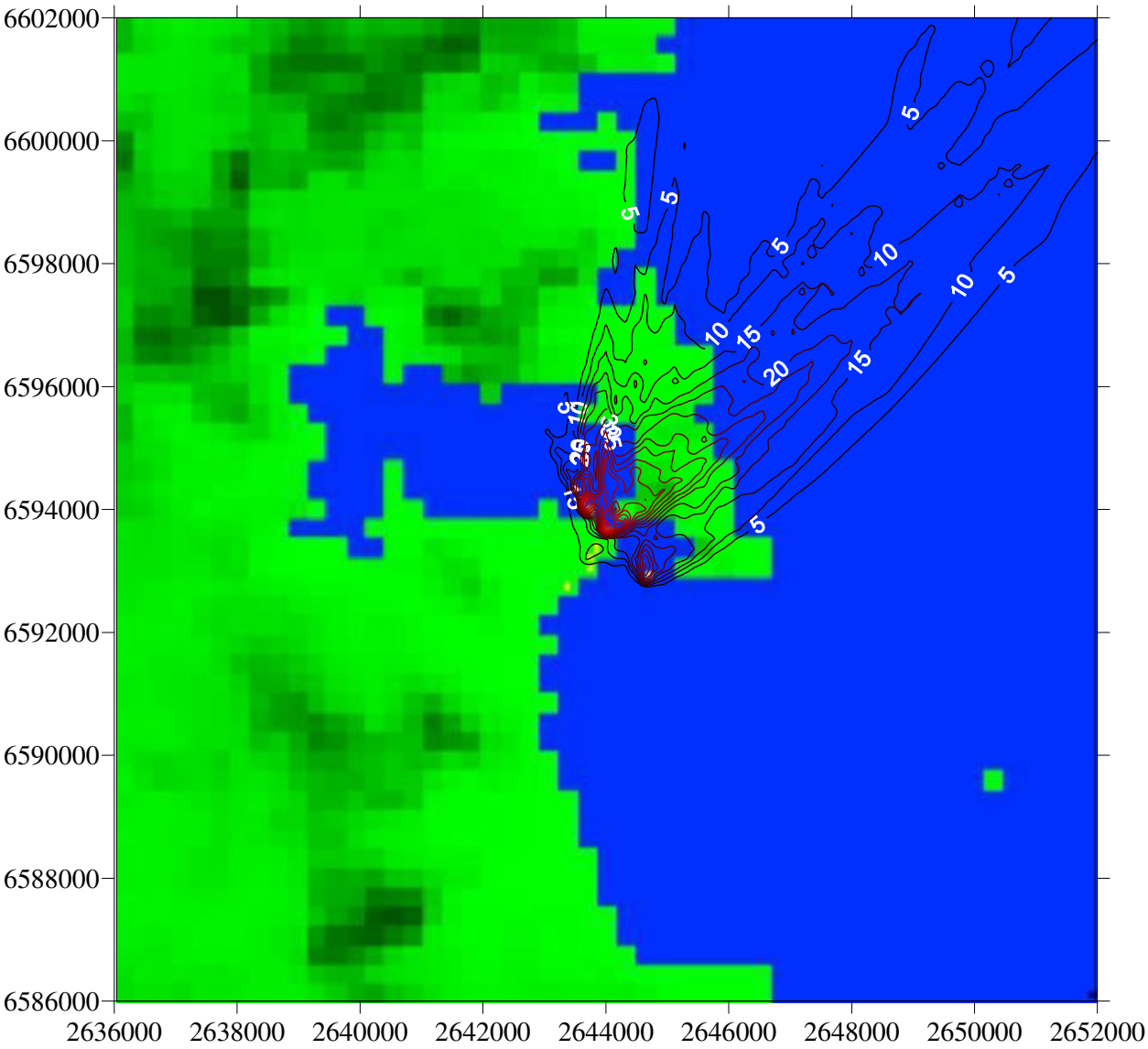

Figure 6.1 **Spatial distribution of modelled ground-level concentrations of SO_2 for Scenario 1 (99.9^{th} percentile values) within the Marsden Point airshed for the two-day simulation period of 6th and 7th June 2005. Relevant parameters: 1-hour time average, spatial resolution of 1 km, concentration values in µg m^{-3} and New Zealand Map Grid coordinates (metres).**

Figures 6.1 and 6.2 show that for the simulation of all sources, highest concentrations occur near the sources and that a south-westerly wind direction exerted its influence over the spatial variability of modelled concentrations. Figure 6.2 shows that when maximum values are included, plotted concentration contours are extended to cover more of the airshed and also display more south and south-easterly wind directions and their influence on the spatial variability of concentrations from the modelled emission sources.

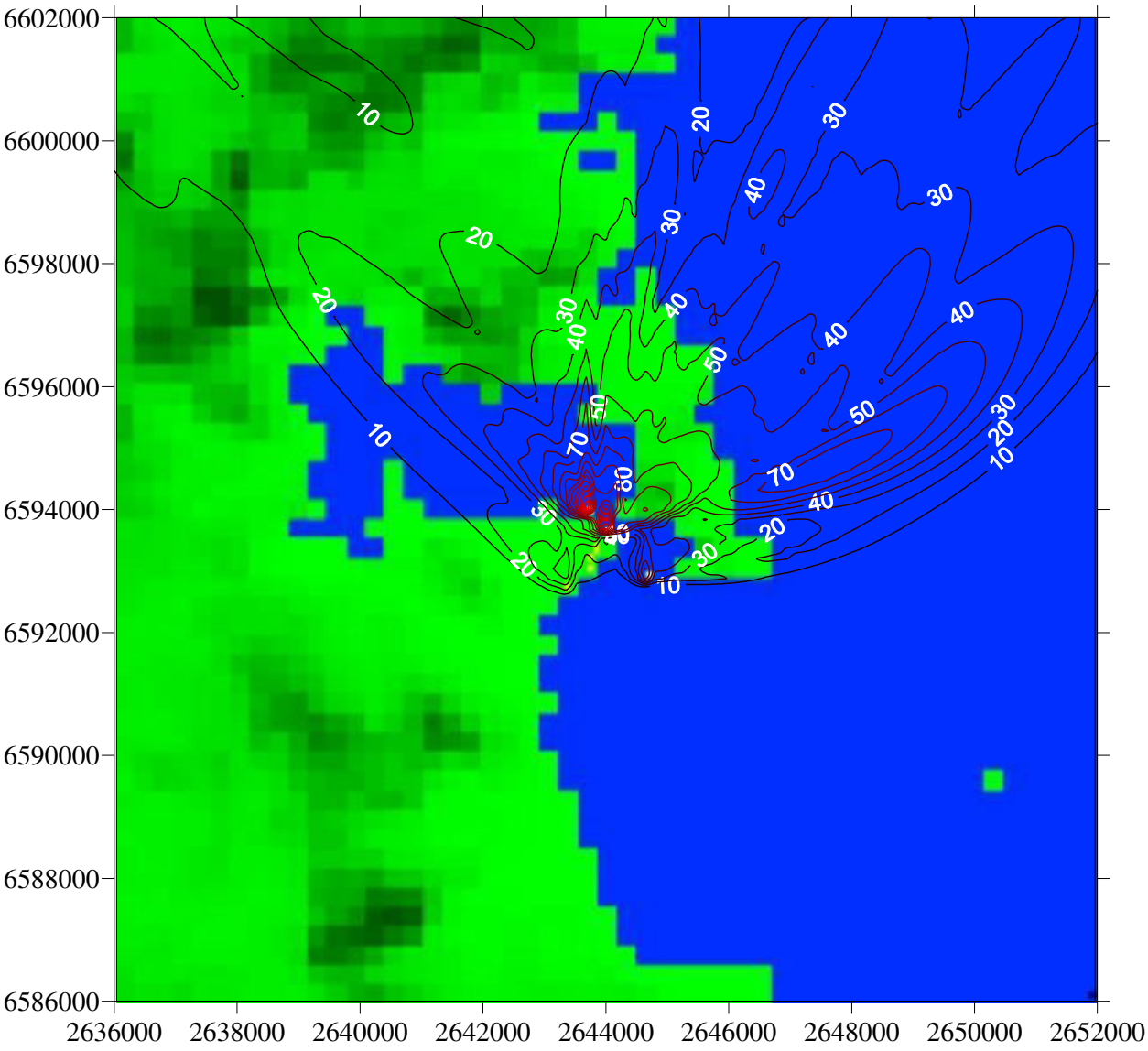

Figure 6.2 **Spatial distribution of modelled ground-level concentrations of SO_2 for Scenario 1 (maximum values) within the Marsden Point airshed for the two-day simulation period of 6th and 7th June 2005. Relevant parameters: 1-hour time average, spatial resolution of 1 km, concentration values in µg m^{-3} and New Zealand Map Grid coordinates (metres).**

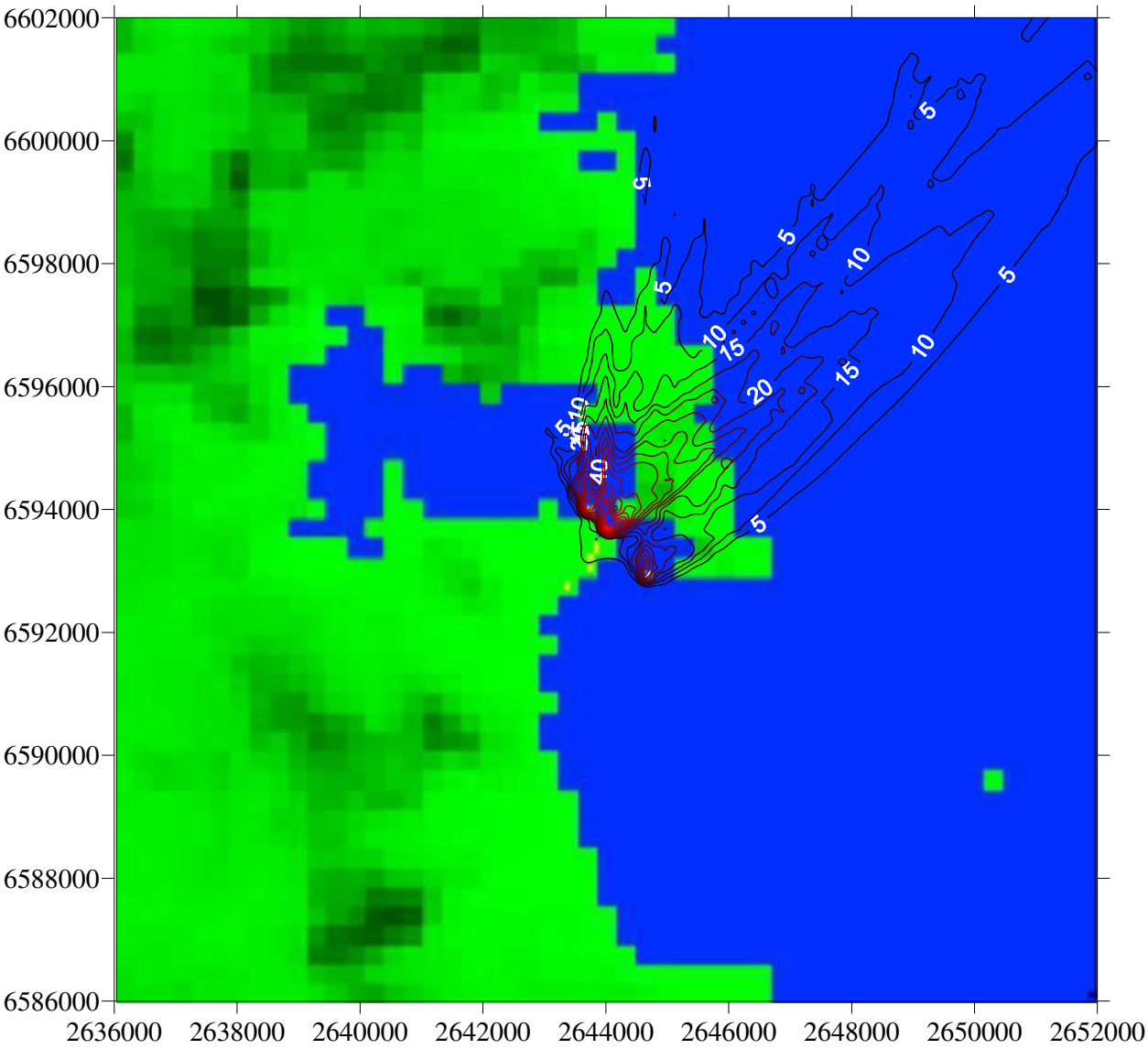

Figure 6.3 **Spatial distribution of modelled ground-level concentrations of SO_2 for Scenario 2 (99.9th percentile values) within the Marsden Point airshed for the two-day simulation period of 6th and 7th June 2005. Relevant parameters: 1-hour time average, spatial resolution of 1 km, concentration values in µg m^{-3} and New Zealand Map Grid coordinates (metres).**

Figures 6.3 and 6.4 show that for the simulation of all sources minus that of Marsden B, highest concentrations again occur near the sources and that a south-westerly wind direction again exerted its influence over the spatial variability of modelled concentrations. Figure 6.4 shows that when maximum values are included, plotted concentration contours are extended to cover more of the airshed and also display more south and south-easterly wind directions and their influence on the spatial variability of concentrations from the modelled emission sources. The results of this scenario are very similar to that of scenario 1 and highlight the lack of influence that Marsden B has had on simulated values and the spatial variability of concentrations.

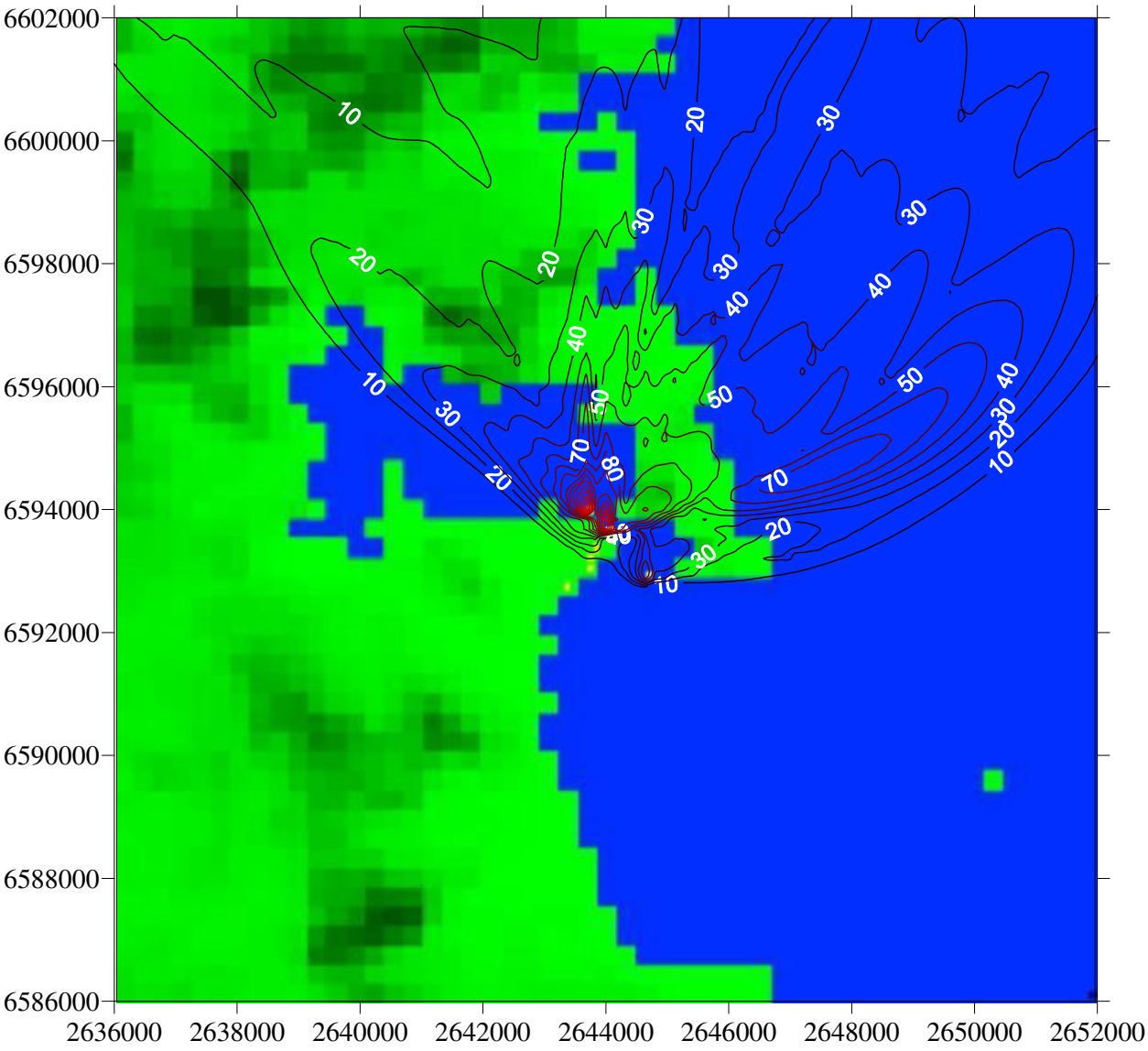

Figure 6.4 **Spatial distribution of modelled ground-level concentrations of SO_2 for Scenario 2 (maximum values) within the Marsden Point airshed for the two-day simulation period of 6th and 7th June 2005. Relevant parameters: 1-hour time average, spatial resolution of 1 km, concentration values in µg m^{-3} and New Zealand Map Grid coordinates (metres).**

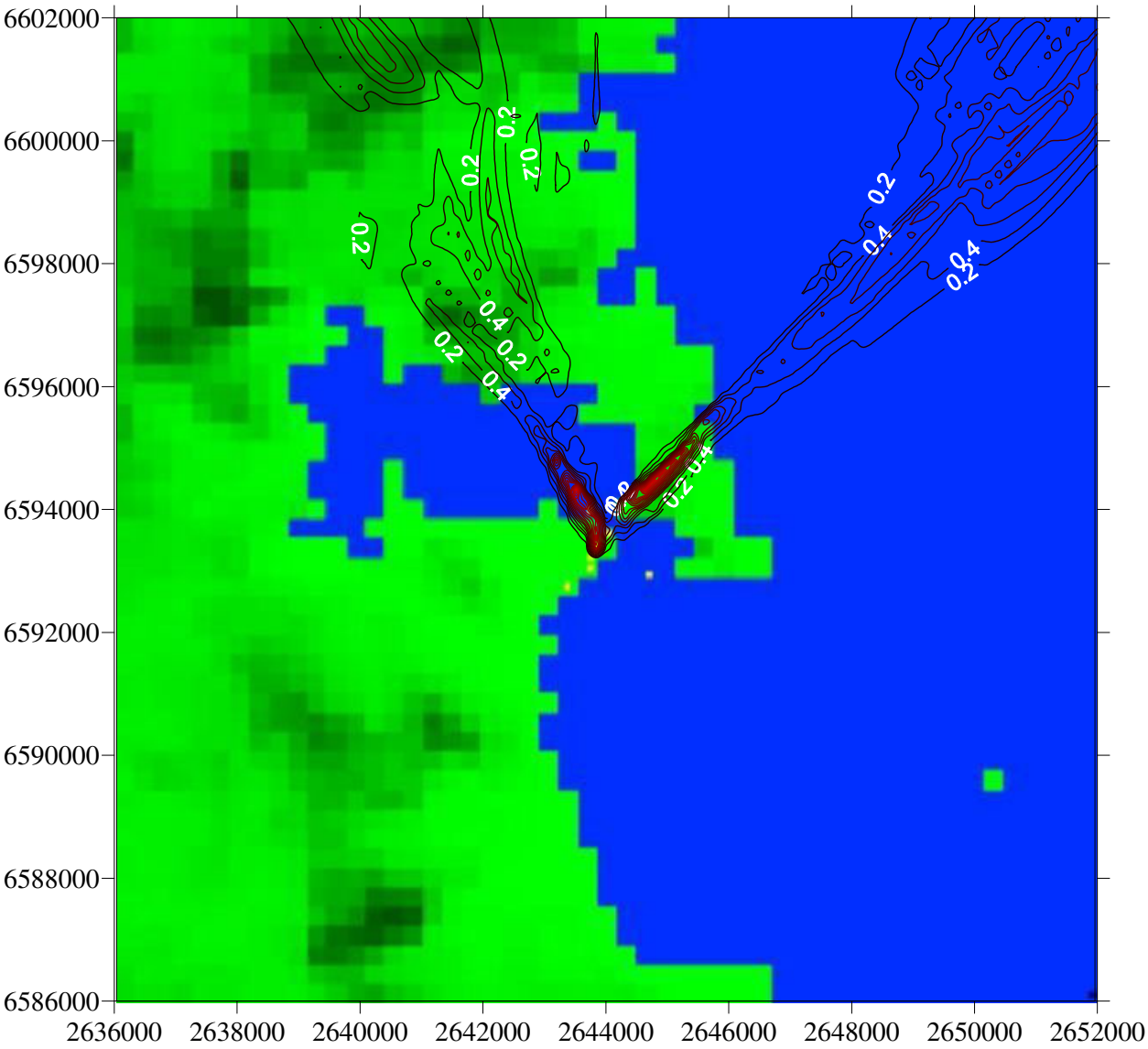

Figure 6.5 **Spatial distribution of modelled ground-level concentrations of SO_2 for Scenario 3 (99.9th percentile values) within the Marsden Point airshed for the two-day simulation period of 6th and 7th June 2005. Relevant parameters: 1-hour time average, spatial resolution of 1 km, concentration values in µg m^{-3} and New Zealand Map Grid coordinates (metres).**

Figures 6.5 and 6.6 show that for the simulation of NZRC only, highest concentrations, although low, again occur near the sources but that some impinging of concentrations can be seen occurring on the raised topography of the Bream Head Peninsula and also just north of the site. The south-westerly wind direction is again exerting its influence over the spatial variability of modelled concentrations, but unlike other plotted 99.9th percentile values, is also causing plumes to head north to north-east of the site also. Figure 6.6 shows that when maximum values are included, plotted concentration contours are again extended to cover more of the airshed and also display more south and south-easterly wind directions and their influence on the spatial variability of concentrations from the modelled emission sources.

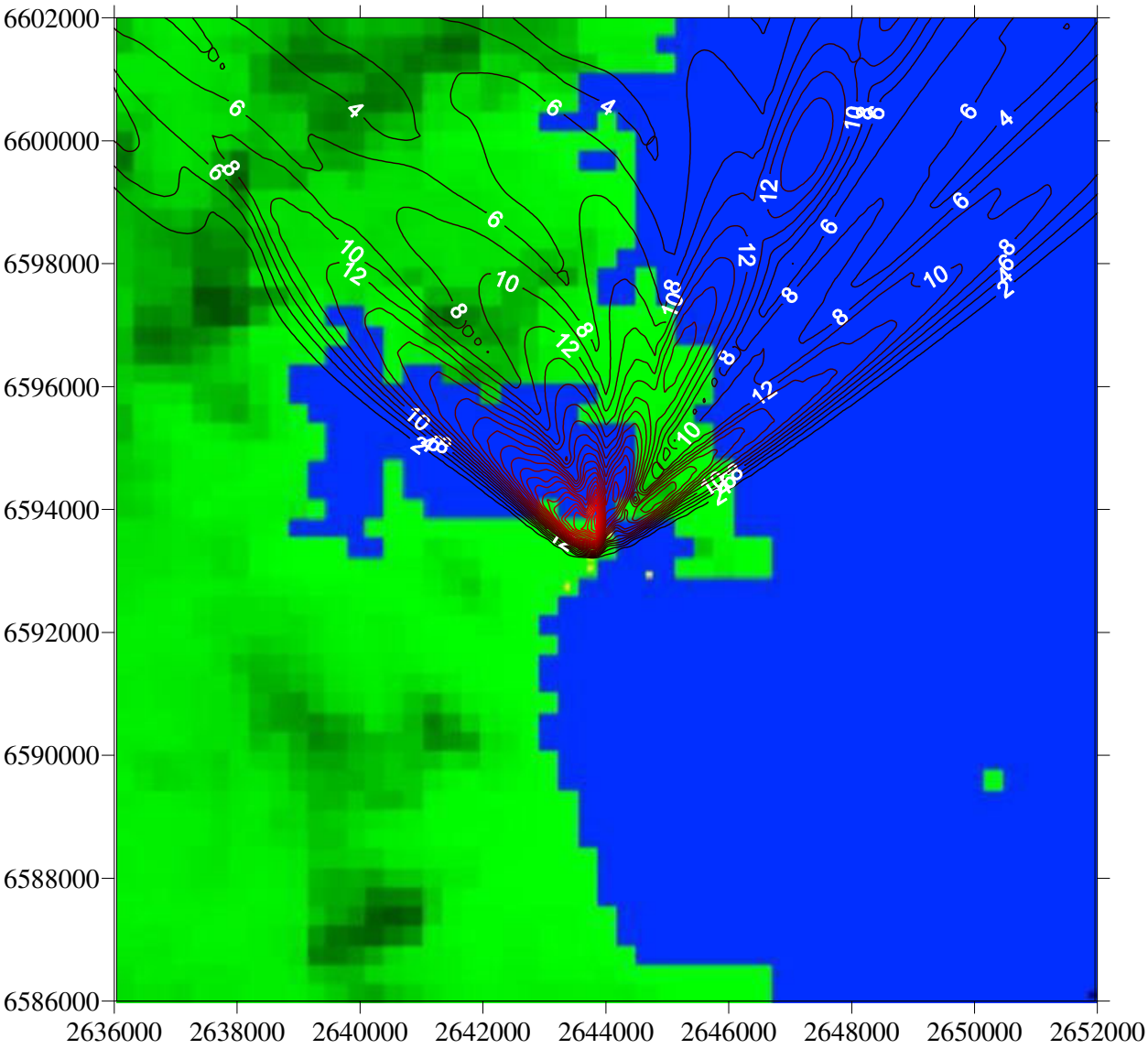

Figure 6.6 **Spatial distribution of modelled ground-level concentrations of SO_2 for Scenario 3 (maximum values) within the Marsden Point airshed for the two-day simulation period of 6th and 7th June 2005. Relevant parameters: 1-hour time average, spatial resolution of 1 km, concentration values in µg m^{-3} and New Zealand Map Grid coordinates (metres).**

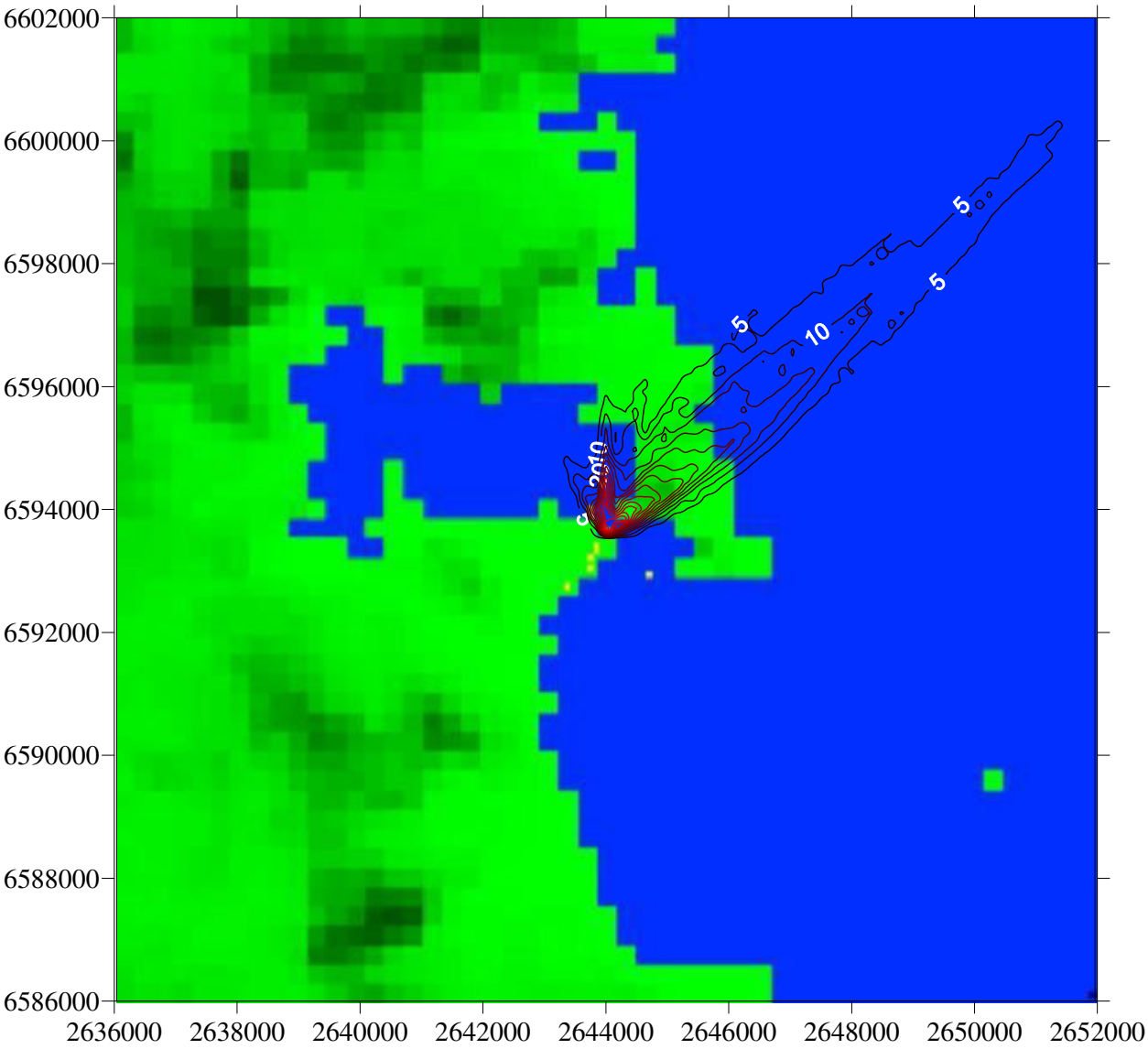

Figure 6.7 **Spatial distribution of modelled ground-level concentrations of SO_2 for Scenario 4 (99.9th percentile values) within the Marsden Point airshed for the two-day simulation period of 6th and 7th June 2005. Relevant parameters: 1-hour time average, spatial resolution of 1 km, concentration values in µg m^{-3} and New Zealand Map Grid coordinates (metres).**

Figures 6.7 and 6.8 show that for the simulation of NZRC plus NZRC Jetty 1, highest concentrations again occur near the sources but that values have substantially increased with the incorporation of a shipping source. Impinging of concentrations on the raised topography of the Bream Head Peninsula is also not as evident in this scenario. The south-westerly wind direction is again exerting its influence over the spatial variability of modelled concentrations. Figure 6.8 shows that when maximum values are included, plotted concentration contours are again extended to cover more of the airshed and also display more south and south-easterly wind directions and their influence on the spatial variability of concentrations from the modelled emission sources.

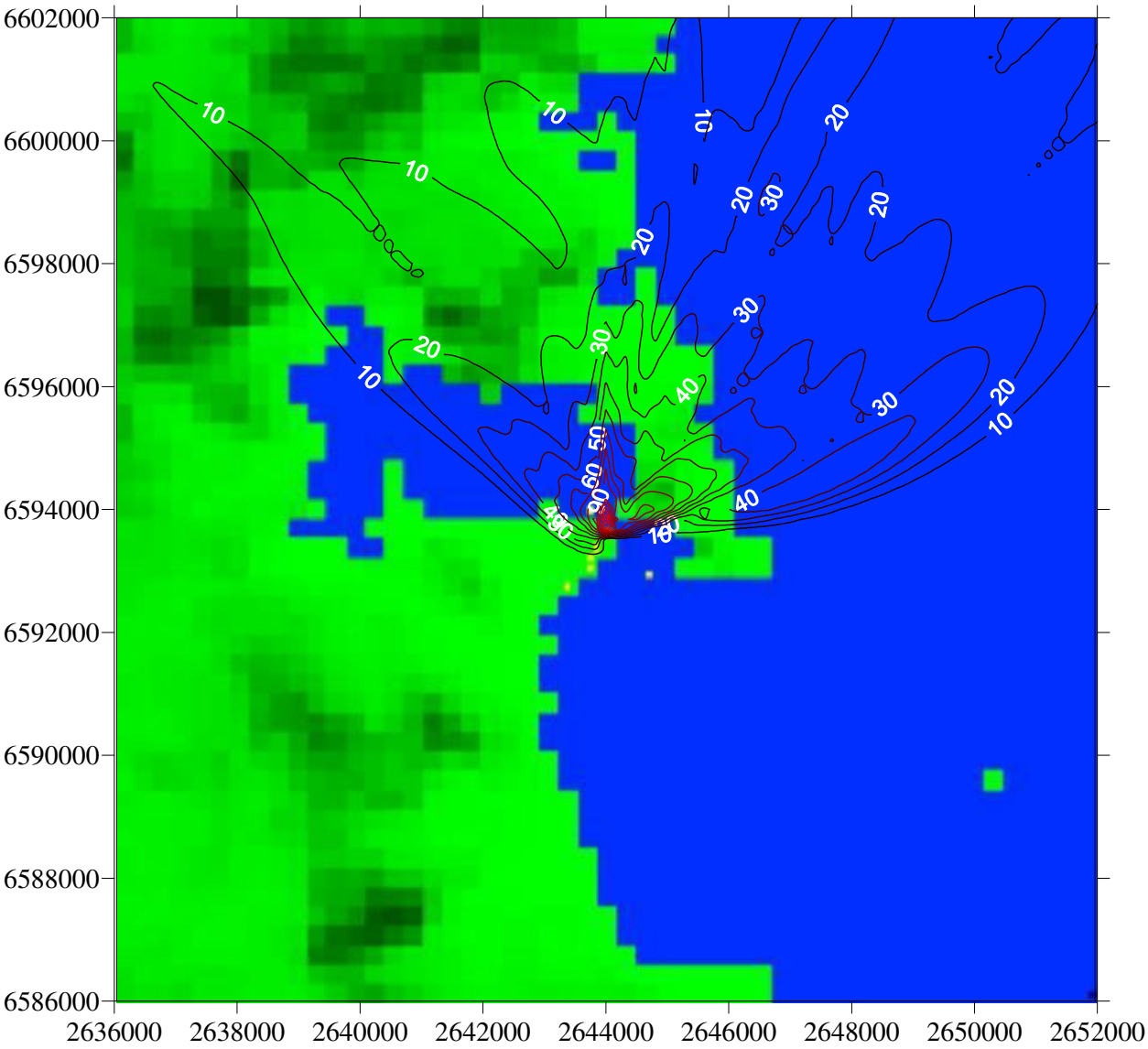

Figure 6.8 **Spatial distribution of modelled ground-level concentrations of SO_2 for Scenario 4 (maximum values) within the Marsden Point airshed for the two-day simulation period of 6th and 7th June 2005. Relevant parameters: 1-hour time average, spatial resolution of 1 km, concentration values in µg m^{-3} and New Zealand Map Grid coordinates (metres).**

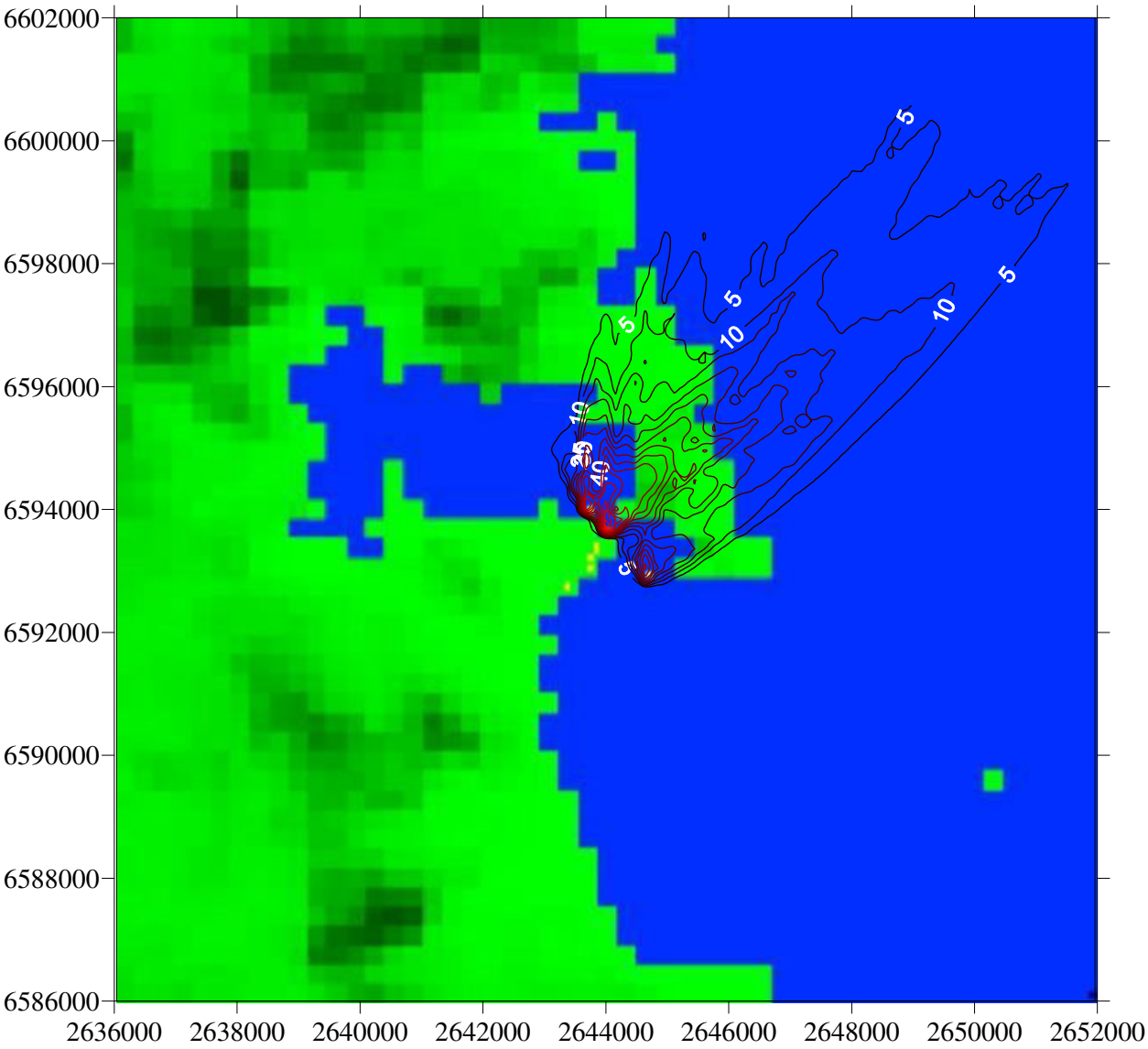

Figure 6.9 **Spatial distribution of modelled ground-level concentrations of SO_2 for Scenario 5 (99.9th percentile values) within the Marsden Point airshed for the two-day simulation period of 6th and 7th June 2005. Relevant parameters: 1-hour time average, spatial resolution of 1 km, concentration values in µg m^{-3} and New Zealand Map Grid coordinates (metres).**

Figures 6.9 and 6.10 show that for the simulation of shipping emissions only, highest concentrations again occur near the sources and that values have again increased with the addition of two more shipping sources. The south-westerly wind direction is again exerting its influence over the spatial variability of modelled concentrations. Figure 6.10 shows that when maximum values are included, plotted concentration contours are again extended to cover more of the airshed but also display increased concentrations just east of the Bream Head Peninsula as well as on the peninsula itself.

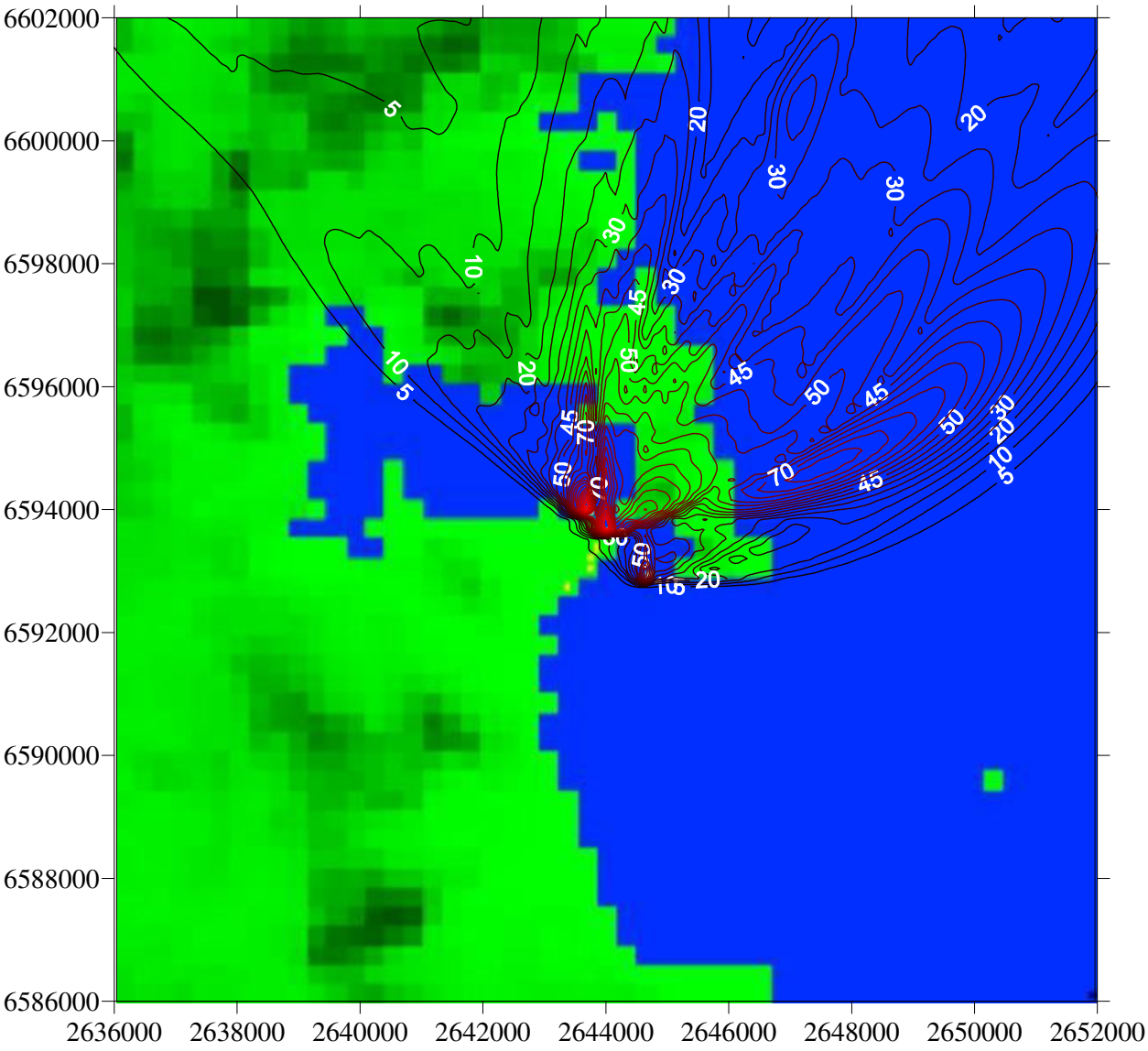

Figure 6.10 **Spatial distribution of modelled ground-level concentrations of SO_2 for Scenario 5 (maximum values) within the Marsden Point airshed for the two-day simulation period of 6th and 7th June 2005. Relevant parameters: 1-hour time average, spatial resolution of 1 km, concentration values in µg m^{-3} and New Zealand Map Grid coordinates (metres).**

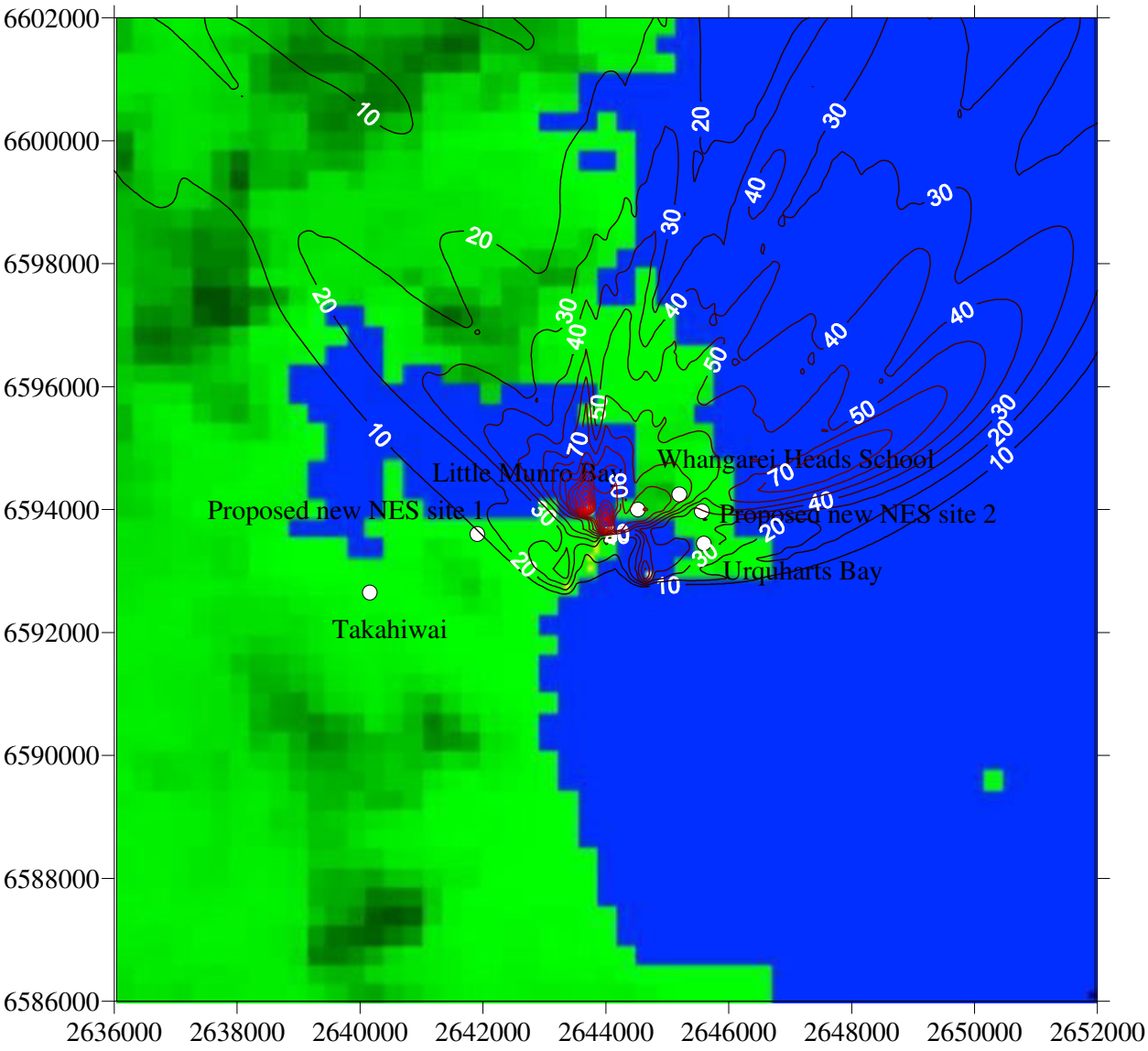

Figure 6.11 Spatial distribution of modelled ground-level concentrations of SO_2 for Scenario 1 (maximum values) overlaying present-day and proposed SO_2 monitoring site locations within the Marsden Point airshed for the two-day simulation period of 6th and 7th June 2005. Relevant parameters: 1-hour time average, spatial resolution of 1 km, concentration values in µg m^{-3} and New Zealand Map Grid coordinates (metres).

The spatial distribution of the modelled ground-level concentrations can be attributed to the characteristics of the plume discharge, meteorology, source alignment and terrain. The pattern of concentrations for all contour maps appears as expected due to the prevailing south-westerly wind direction, thus producing the pattern around the southwest-northeast axis. This pattern of modelled wind direction influencing the appearance of the contour maps is supported by the Whangarei Airport recorded wind conditions for the simulated dates (see Figure 5.8), plus that of the synoptic chart which saw a strong south-westerly flow over most of the country for the simulated time period (see Figure 5.10). Both the 99.9th percentile and maximum value plots for

each scenario show the south-westerly wind at work, with the maximum value plots also displaying more south and south-easterly wind directions and their influence on the spatial variability of concentrations from the modelled emission sources.

The three shipping sources (modelled as point sources as per the industrial sources) associated with the airshed study are aligned approximately in a northwest - southeast direction, also reinforcing the contour patterns. There is also significant topography on the downwind side of the bay that may cause compacting of the plume. The impacts of ship emissions can be of greater concern in some areas than in others, where local topography and microclimate can exacerbate the effect caused by pollutant emissions.

For the most part, the modelled concentrations appear to simply reduce as the contours appear further away from the sources. The highest modelled concentrations are at or near the largest emitters, but there is also some evidence of concentrations impinging on the complex topography downwind of the sources, indicating that raised concentrations can result from the plume impacting on the higher terrain. The Marsden Point airshed area incorporates a number of elevated terrain features located on Bream Head Peninsula. These features are important both because of the potential for high pollutant concentrations to occur on them, and for the effects they have on local meteorological conditions. Significant terrain features include hills to the north of Whangarei Harbour, namely Mt. Manaia, Mt. Aubrey and Mt. Lion, which range in height from 210m to 470m. Hills to the west and south-west (Ruakaka Forest) range in height from 200m to 260m. Sensitive receptors, such as schools and residential properties are also located on the peninsula.

A few issues may play a part in the lack of impingement of modelled concentrations on these hills for every plotted scenario. Firstly, the behaviour of emitted plumes can be expected to be quite complex under the meteorological and topographical conditions presented within this particular airshed. It could also be suggested that the model has failed to see in every instance the significant topographic features of the area at a grid resolution of 1000m. Also, it is feasible to suggest that the combined and enhanced buoyancy associated with emissions from several sources close together will aid in a higher plume rise and may have contributed to lifting plumes over the complex topography of this airshed, resulting in lower ground-level concentrations. Manins *et al*. (1992) demonstrated that plume rise could be enhanced by 10 to 45% by the presence of multiple stacks. Having said that, five of the eight emission sources emit to atmosphere via shorter stacks (10 - 30m agl), but the NZRC and Marsden B stacks are all in

excess of 100m in height. It is also important to note that a very limited number of events have been modelled - only two days. Additionally, the practice of removing the highest 0.1% of predictions in order to present 99.9th percentile values as the most likely maximum ground-level concentrations to occur may have removed the higher values impinging on the hills, and hence one reason for including maximum modelled values for comparison in Table 6.1.

6.2 Shipping

Modelled emissions from the three shipping point sources using TAPM for the 2-day simulation period associated with this case study have proven to be the 'surprise package' regarding resultant concentrations. The impacts of ship emissions can be of greater concern in some areas than in others, where local topography and microclimate can exacerbate the effect caused by pollutant emissions, and it would appear that the Marsden Point airshed, with its elevated terrain features located on Bream Head Peninsula, is one such area. The comparatively low stack heights of the shipping sources (previously mentioned) and the lower mixing height associated with plumes over water have both contributed to these results.

6.3 New Zealand Refining Company

The lower than expected modelling result for scenario 3 (NZRC only) were initially puzzling. With the highest emission rate (NZRC B & C) of all modelled point sources, it seemed perfectly acceptable to expect higher results. However, where low stack height would appear to be the major criteria governing the higher modelled concentrations associated with shipping, the taller stacks at the NZRC site, coupled with higher exit velocities (increasing vertical momentum) and stack temperatures in excess of 200°C (assisting thermal buoyancy), appear to have aided in producing low values for the 2-day simulation period from this source. When synoptic winds are ignored (see Section 6.8), the plumes from these tall on-shore stacks are possibly dragged down by the generally lower mixing heights associated with flows over water. Mixing heights are higher over land during the day and lower during the night relative to water. The temperature of land fluctuates, whereas for a water body it is constant. With no calm wind periods being experienced during the modelling simulation period, and an average wind speed of 3.85 m s^{-1}, conditions were conducive to good dispersion of plumes emitted at higher elevations. Modelling of the NZRC sources over an extended time period with an examination of trends and different scenarios (e.g. 'minor process upset' - Figure 5.20) may result in more 'interesting' results in comparison to the values produced here from a study impaired by several limitations.

6.4 Modelling v monitoring

Given that emissions from all sources are set to maximum (i.e. discharge licence limits), it is surprising to find that maximum modelled concentrations do not reach as high a value as that measured at anytime. The modelled 1-hour average ground-level concentration for SO_2 from Scenario 1 (all sources), grid 4 (horizontal resolution = 1km) is listed in Table 6.2, and compared with the hourly average concentration derived from Whangarei Heads School monitoring records for June 6th and 7th, 2005.

Table 6.2 1-hour averaged SO_2 modelled value (scenario 1) and 1-hour monitored value from Whangarei Heads School: June 6th - 7th, 2005.

Scenario	Time average	Modelled SO_2 value (µg m^{-3})	Monitored SO_2 value (µg m^{-3})
1 - All sources	1-hour	26	55

Figure 6.12 graphically shows the two-day time series comparison of modelled (scenario 1) values using TAPM plotted against SO_2 concentrations from Whangarei Heads School monitoring records for the 48-hours comprising June 6th and 7th 2005. The TAPM line refers to values extracted from a grid point close to the monitoring station.

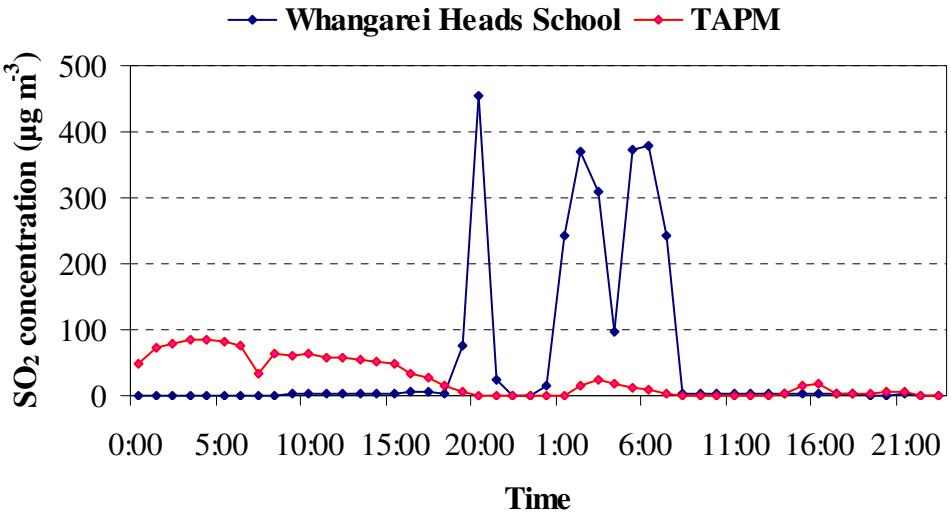

Figure 6.12 Time series comparison of modelled (scenario 1 - all sources) and monitored SO_2 values for the case-study modelling period of 6th and 7th June 2005: 1-hour time average.

Monitoring data from the Whangarei Heads School for the two-day modelling period of 6th and 7th June 2005 has been utilised as a comparison (Table 6.2). Daily monitoring averages for Whangarei Heads School far exceed those recorded at two other monitoring stations (Little Munro Bay and Urquharts Bay), and perhaps help explain in part the lower modelling results when compared to the hourly results from Whangarei Heads School. As can be seen in Figure 6.12, there is not a great deal of agreement between modelled results and actual SO_2 concentrations obtained from Whangarei Heads School monitoring records for the 48-hours comprising June 6th and 7th, 2005. This may suggest an error with the quality of recorded data from the monitoring site, but there is however no good reason to suspect instrumental error as the reason for the very high monitored values between the hours of approximately 1700 hours on the 6th and 0700 hours on the 7th (NZRC records indicate the monitor as working satisfactorily after testing that NZRC emissions were approximately 12t day^{-1} and that meteorological conditions were conducive to limited dispersion of SO_2 emissions during this period). Although there is no direct evidence implicating any one particular source as being responsible for the large increase in monitored concentrations during these hours of the study it is possible that, as was the case with the 'minor process upset' at NZRC during 2005 (possibly during February according to the Council), that a source within the airshed, and quite possibly close to the Whangarei Heads School monitoring site, did indeed expose the monitor to greatly increased levels of SO_2 for a limited time, such as the burning of tyres close by. However, there are no records of complaints being made to the Northland Regional Council during this time. Peaks and troughs in SO_2 concentrations may generally correspond with times when maximum ship movements are occurring, but on average shipping movements into and out of Whangarei Harbour would not occur so frequently over a 12-hour (overnight) period (average vessel berth is 2 days). There may also be the possibility that given the pollution rose plotted in Figure 5.25 that sources outside of the Marsden Point airshed may have contributed to the high recorded SO_2 values at Whangarei Heads School.

One likely reason for the lack of agreement between modelled and monitored concentrations is the model itself. That is, TAPM has been unable to effectively model concentrations given the inclusion of fixed rather than variable emission rates for the industrial point sources. The modelling of a short time period (1-hour) may also be a factor and TAPM may not be as effective in reproducing 1-hour values as it is for longer time averages. If the emission data had been more representative and the meteorology well represented, results for the 1-hour time average simulations may have provided more agreement with monitored values. The over-estimation of TAPM wind speed, approaching double that monitored at the Whangarei Airport

meteorological site (3.85 ms^{-1} compared to 2.00 ms^{-1}) for the simulation period is another area where TAPM has failed to reproduce actual values and consequently added to the poor agreement between modelled and monitored concentrations of sulphur dioxide in the Marsden Point airshed for the two-day modelling period, the short time period itself being a major limitation of this case-study. These two days however were chosen for several reasons:

- One-hour monitored concentrations of SO_2 at the Whangarei Heads School site were made available for comparison with modelled concentrations for these dates.
- High concentrations of SO_2 had been measured at the Whangarei Heads School monitoring site for June 6th and 7th 2005.
- Higher daily average SO_2 monitoring values for October 2005 were recorded at the Whangarei Heads School site, however one-hour monitored concentrations at this site were not made available for dates other than June 6th and 7th 2005, or for other pollutants.
- Daily (24-hour) monitored concentrations were made available for other dates, but the aim was to assess the modelled concentrations of SO_2 with reference to the NES for SO_2, which has an hourly average attached to it.
- The Good Practice Guide for Atmospheric Dispersion Modelling (Bluett *et al*., 2004) recommends that case-studies be examined over a period of one to three days. The Guide also recommends a spatial resolution of 1 to 3 km's as being typical and for an hourly time resolution. These points are all consistent with the thesis modelling case-study.
- Performing long-term high-resolution simulations with multiple point sources is prohibitive due to computational demands.

6.5 Meteorological data

To validate the generation of meteorological data extracted from the corresponding TAPM grid cells, a comparison has been made with monitored meteorological data from the closest reliable (i.e. calibrated) meteorological station - Whangarei Airport. Figures 6.13 to 6.16 summarise the results for hourly wind speed, wind direction, temperature and relative humidity, as used in this case study. Figure 6.17 shows the frequency distribution of occurrences of winds for each direction sector and for each wind class (wind rose) as generated by TAPM for June 6th and 7th 2005, resulting in a strong south-westerly flow, which is consistent with the synoptic chart conditions shown in Figure 5.10 and Whangarei Airport measured wind conditions for the same time period in Figure 5.8. Figure 6.18 shows the TAPM generated wind class frequency distribution as a percentage for the same dates. TAPM has failed to simulate a period when wind

conditions at Whangarei Airport were recording a north-westerly wind direction for a certain period of the case-study simulation and an over-estimation of wind speed by TAPM, where no calm wind periods were simulated compared to 2.22% calm periods being recorded at the Whangarei Airport meteorological site, has also resulted in only reasonable agreement between the two.

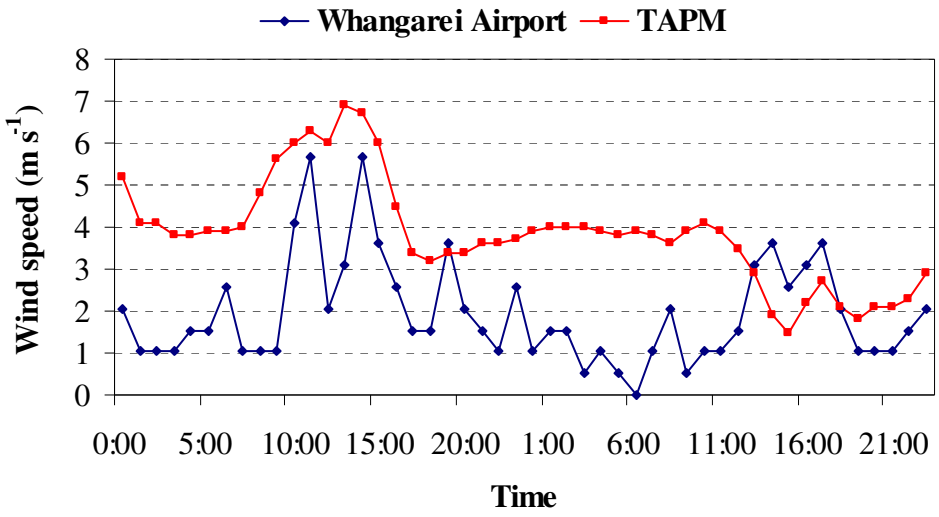

Figure 6.13 Time-series comparison of monitored and modelled wind speed for the case-study modelling period of 6th and 7th June 2005.

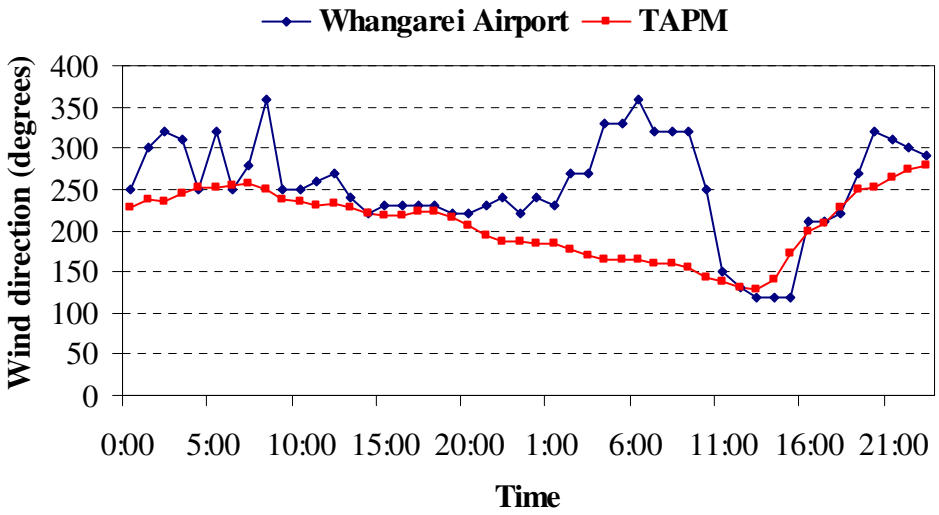

Figure 6.14 Time-series comparison of monitored and modelled wind direction for the case-study modelling period of 6th and 7th June 2005.

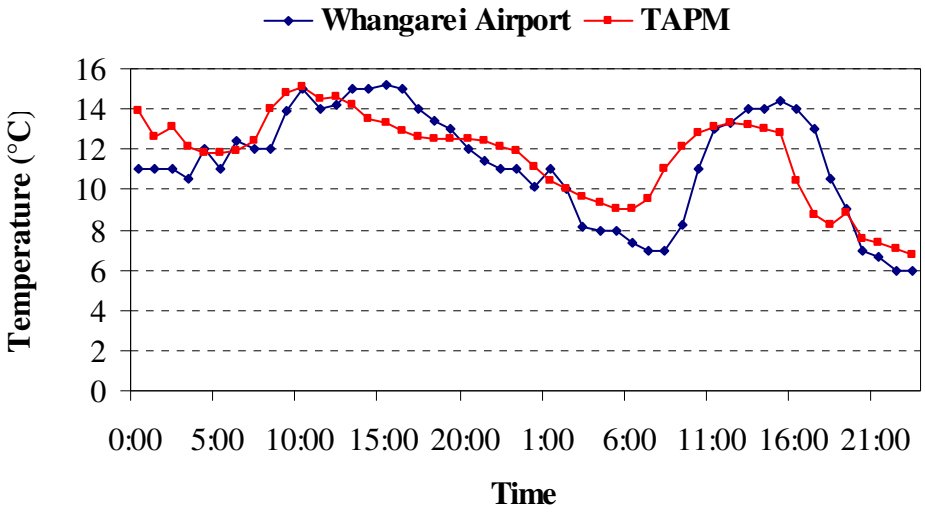

Figure 6.15 Time-series comparison of monitored and modelled temperature for the case-study modelling period of 6th and 7th June 2005.

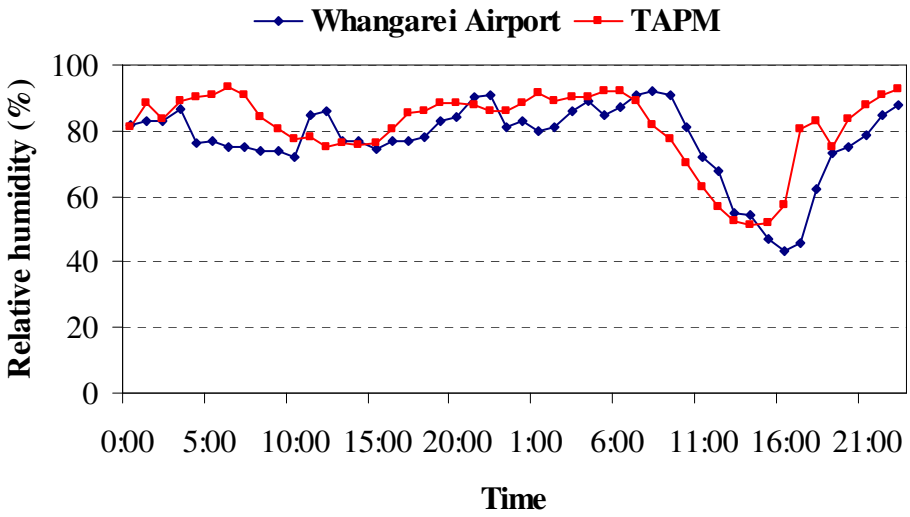

Figure 6.16 Time-series comparison of monitored and modelled relative humidity for the case-study modelling period of 6th and 7th June 2005.

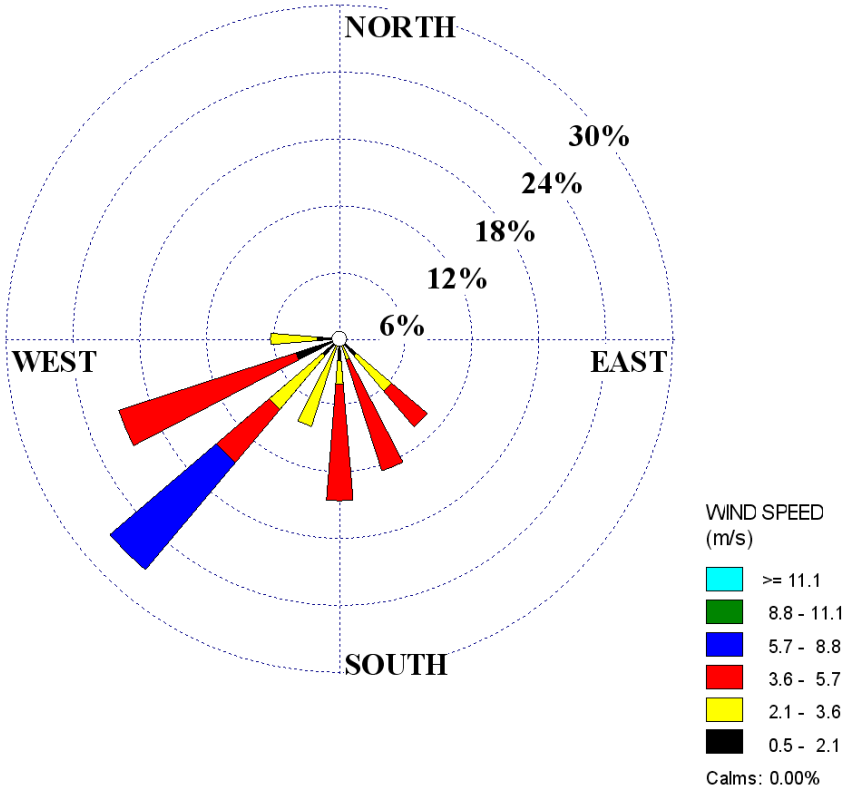

Figure 6.17 **TAPM generated wind rose for June 6th and 7th 2005, showing the frequency of winds from given directions and in a range of speed classes. Note: 'Calms' = 0.00%.**

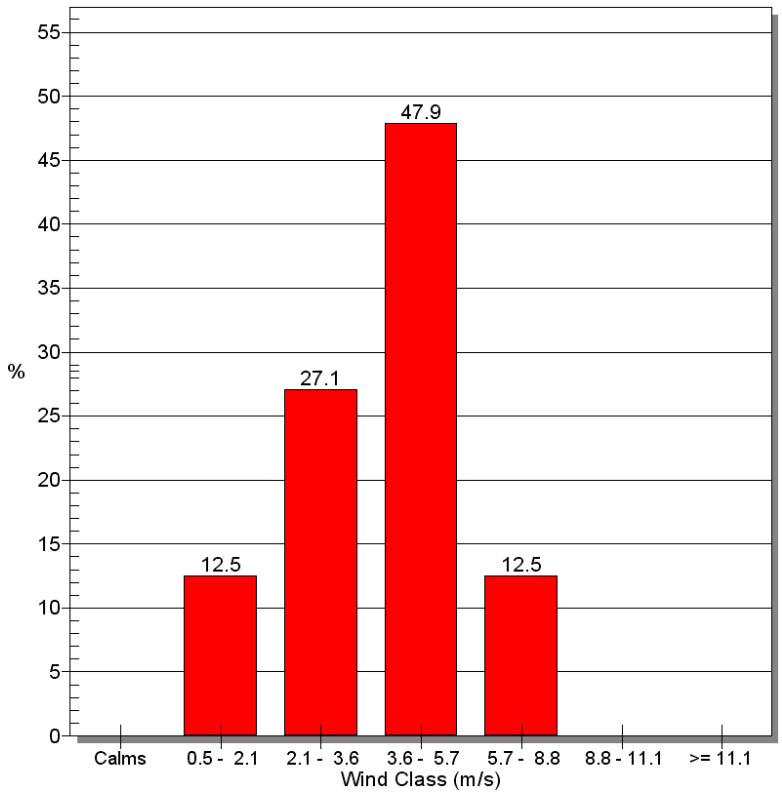

Figure 6.18 **TAPM generated wind class frequency distribution for June 6th and 7th 2005. Average wind speed = 3.85 m s^{-1}.**

6.6 Summary statistics and Index of Agreement

An index of agreement (IOA) has been calculated, which summarises the graphical comparisons in a tabular format. Table 6.3 summarises the calculated IOA for wind speed, temperature and relative humidity, plus other meteorological summary statistics. Values above 0.50 for IOA are considered to be of reasonable agreement.

Table 6.3 Summary statistics and Index of Agreement for TAPM modelling case-study of Marsden Point airshed - 6th and 7th June 2005.

Statistics	Wind speed (ms^{-1})		Temperature (°C)		Relative humidity (%)	
	Observed	TAPM	Observed	TAPM	Observed	TAPM
Arithmetic mean	1.9	3.8	11.3	11.6	77.3	81.2
Standard deviation	1.2	1.3	2.7	2.2	11.8	11.4
Minimum	0.0	1.5	6.0	6.8	43.0	51.1
Maximum	5.7	6.9	15.2	15.1	92.0	93.0
n	48		48		48	
RMSE [1]	2.40		1.68		9.82	
Corr [2]	0.33		0.79		0.69	
SKILL_V [3]	1.08		0.81		0.97	
SKILL_R [4]	2.00		0.62		0.83	
IOA	**0.49**		**0.88**		**0.80**	

[1] Root Mean Square Error. [2] Pearson Correlation Coefficient (0 = no correlation, 1 = exact correlation).
[3] (SD_TAPM)/(SD_Observed) - near to 1 shows skill. [4] (RMSE)/(SD_Observed) - <1 shows skill.

The Index of Agreement (IOA) is a measure of how well predicted variations about the observed mean are represented for selected meteorological parameters, with a value greater than about 0.50 considered to be good, as judged by several other published prognostic modelling studies (Hurley *et al*., 2002). The meteorological results of this study indicate that TAPM predicts parameters such as temperature and relative humidity with sufficient accuracy, although there is room for improvement when assessing agreement between the modelled wind speed and the monitored equivalent from the Whangarei Airport meteorological station. Although an IOA value of 0.49 for wind speed can be considered reasonable given that 0.50 is good, this lower value when compared to those for temperature and relative humidity may highlight the unresolved debate surrounding mesoscale models such as TAPM, and their ability to sufficiently handle 'calms' (periods when wind speeds are less than approximately 0.5 m s^{-1}). Inabilities to accurately predict wind speed will in-turn have an effect on predicted wind direction and ultimately produce less agreement with monitored values. Having said that, TAPM generated calm periods of less than 0.5 m s^{-1} for the modelled dates are non-existent. The minimum

generated wind speed is 1.5 m s^{-1} (still low) with an average wind speed across the 48-hours of 3.85 m s^{-1}. The Whangarei Airport meteorological station recorded an average wind speed of 1.93 m s^{-1} for the same time period.

6.7 Modelled winds

TAPM generated GIS (Geographic Information System) graphics are shown in Figures 6.19 and 6.20 to highlight the change in the modelled wind direction which occurs at approximately the same time (1700 hours on 6th June) as peaks in concentrations begin to appear at the Whangarei Heads School monitoring site. Modelled winds had been consistently blowing from the south-west up until this time, but appear to change to a more south and south-easterly direction. On-shore easterly winds are also seen blowing through the harbour entrance. This is the case until approximately 1500 hours on 7th June, when winds resume blowing from a more west and south-westerly direction. The temporary change in wind direction as generated by the model also took the emission plumes away from the hills downwind of the prevailing winds and subsequently reduced resultant modelled concentrations in these areas and also affected agreement between modelled and monitored SO_2 concentrations. Figures 6.19 and 6.20 also highlight the influence of elevated terrain in the airshed, both on the Bream Head Peninsula and to the west of Marsden Point at Ruakaka Forest, where channelling of the wind can be seen. TAPM has also failed to simulate the period when wind conditions at Whangarei Airport were recorded to be blowing from the north-west for approximately 15% of the case-study simulation period (see Figure 5.8) and also over-estimated wind speed for the simulation dates. This topic is further discussed in Section 7.8.

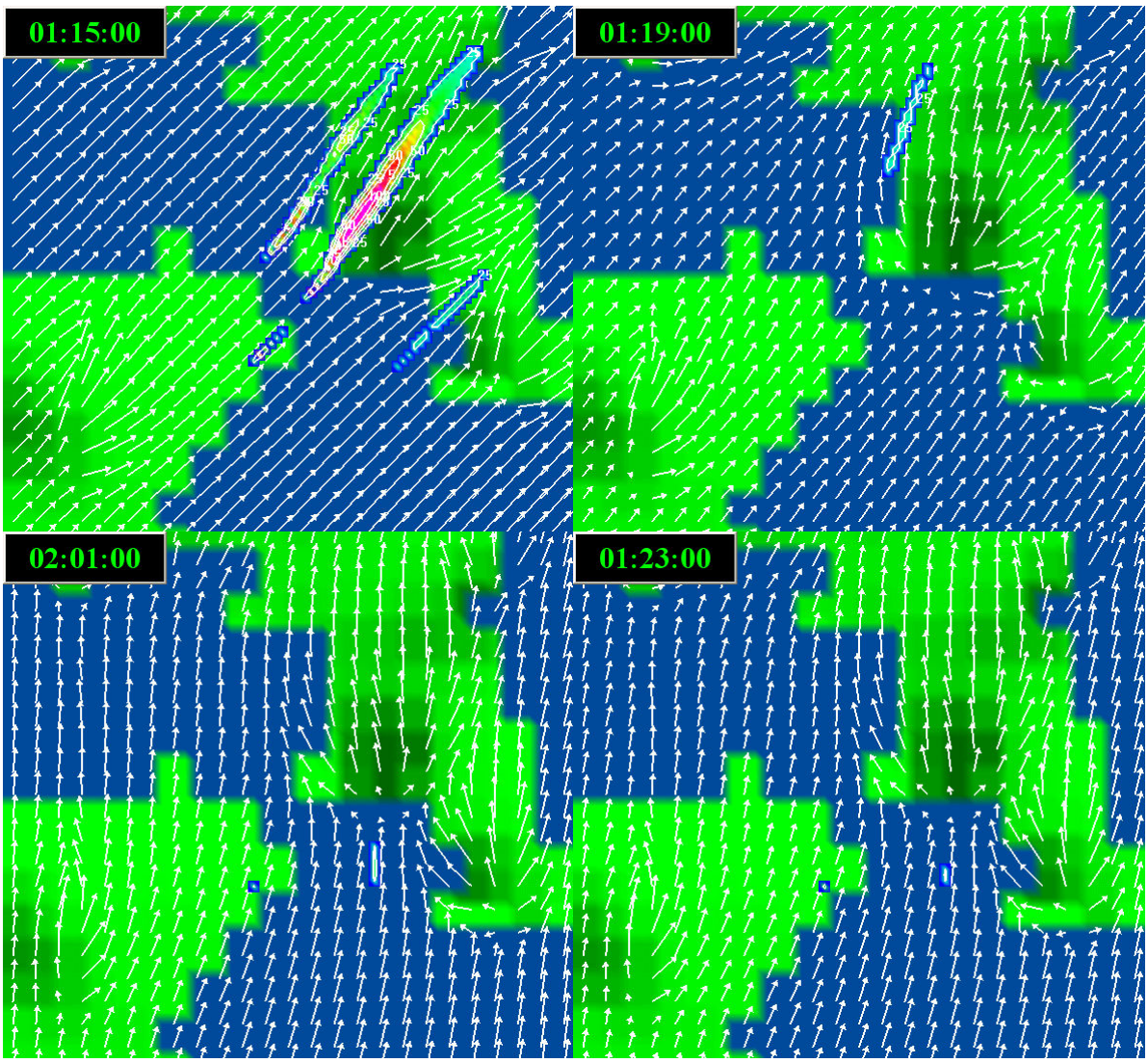

Figure 6.19 **GIS screen snapshots displaying TAPM generated wind direction and speed (length of arrow) on day 1 (6th June) at (clock-wise from top left) 1500, 1900 and 2300 hours and 0100 hours on day 2 (7th June).**

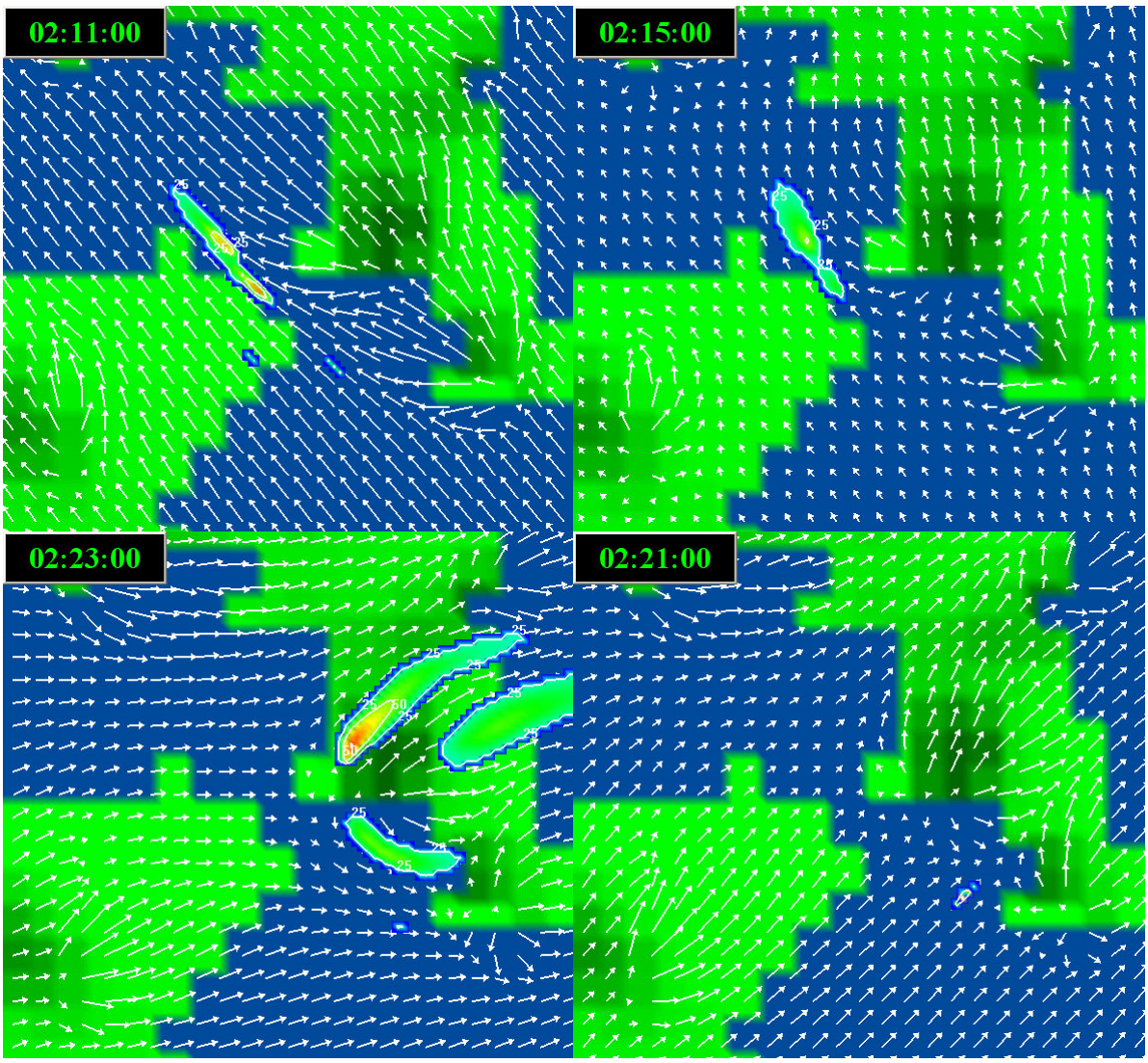

Figure 6.20 GIS screen snapshots displaying TAPM generated wind direction and speed (length of arrow) on day 2 (7th June) at (clock-wise from top left) 1100, 1500, 2100 and 2300 hours.

6.8 Idealised model run

An idealised simulation with TAPM run has been generated in order to compare the differences in wind behaviour that occur when synoptic winds are ignored and the resultant effect on modelled concentrations. The atmosphere is assumed to be at rest for the duration of such a run, therefore any flow (local wind) that is generated is due to surface heating and cooling, commonly referred to as terrain-induced (or thermally-induced) circulations. Local winds are prevalent during stagnant atmospheric conditions when the potential for poor air quality is highest. Therefore such a simulation could potentially produce the highest possible ground level concentrations in an airshed. For the idealised simulation input files were prepared where the wind speed for the atmosphere was set to zero, and the standard temperature and humidity profiles were chosen for the entire domain. Boundary conditions were set to zero gradient.

Figure 6.21 shows wind direction and speed (represented by the length of the arrow) as it was generated by TAPM with synoptic winds for midnight on day two - 7th June. Figure 6.22 shows wind direction and speed for the exact same time minus the influence of synoptic winds. The resultant concentrations (in parts per billion) associated with both scenarios are also displayed using plotted contour lines. The channelling influence of the Bream Head Peninsula hills and Ruakaka Forest, west of Marsden Point, are evident in both figures.

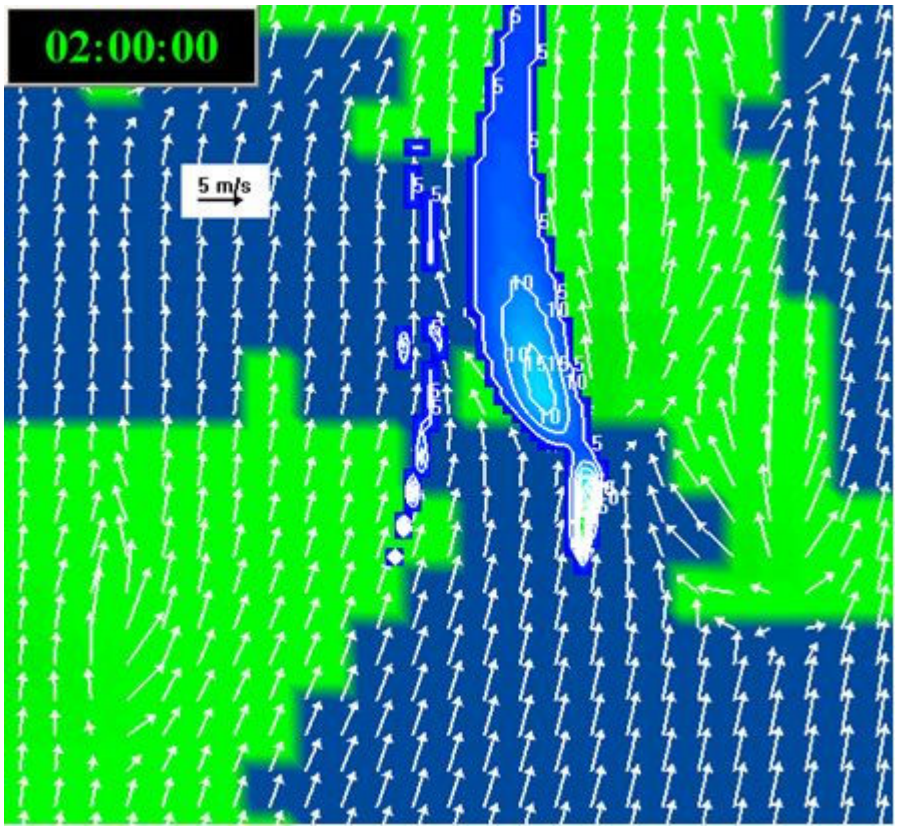

Figure 6.21 GIS screen snapshot showing wind direction, wind speed and resultant SO_2 concentrations (ppb) as generated by TAPM for midnight on 7th June - synoptic winds included.

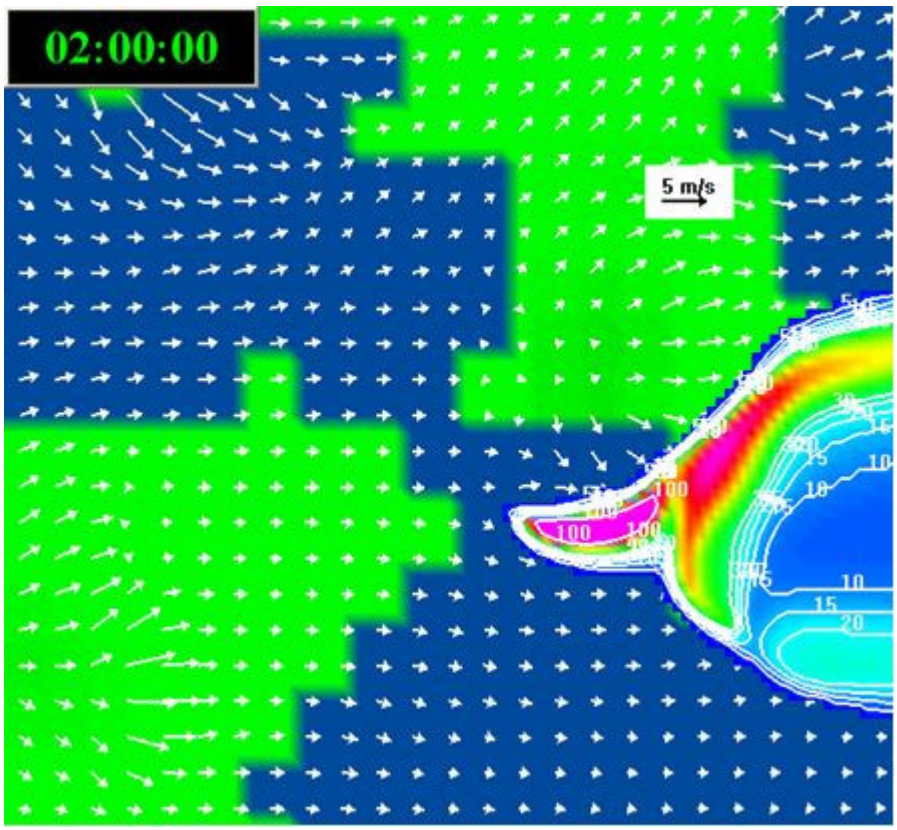

Figure 6.22 GIS screen snapshot showing wind direction, wind speed and resultant SO_2 concentrations (ppb) as generated by TAPM for midnight on 7th June - synoptic winds removed.

Synoptic winds are winds associated with large-scale events and are part of what makes up everyday weather. Removing this influence creates what could be termed a worst-case scenario. Results show a large difference between the run at midnight on day two with synoptic winds included against that of the run that ignored these winds at the same date and time. When synoptic winds are included, wind direction is primarily from the south to south south-west with some altering influences being exerted from the elevated terrain features located on Bream Head Peninsula, and also to the west (upwind) of the NZRC site. When synoptic winds are ignored, wind direction is primarily from the west, but again the aforementioned hills play a part in diverting the flows briefly. Wind speed is also dramatically reduced in this option. As expected, the resultant SO_2 concentrations modelled by TAPM when synoptic winds are ignored are increased substantially when the plumes hit the Bream Head Peninsula, and indeed are also much higher over the water downwind of the NZRC site and before reaching the hills. However, the resultant concentrations are still within the sulphur dioxide National Environmental Standard (NES) for Ambient Air Quality.

6.9 Summary

This chapter has presented results for the two-day modelling case-study of the Marsden Point airshed, Northland, utilising The Air Pollution Model (TAPM). Results, covering modelled and monitored SO_2 concentrations and meteorological conditions for the period of interest have been presented in both tabular and graphical formats and initial interpretations have been introduced. All modelled concentrations of SO_2 in the Marsden Point airshed for the two-day simulation period are within the corresponding National Environmental Standard (NES) for Ambient Air Quality. There is greater agreement between modelled and monitored values for meteorological parameters than there is for SO_2 concentration values for the simulated period. There are several suggestions made as causes for this disparity, but TAPM, using fixed rather than variable emission rates as inputs for the industrial point sources is a likely cause. A temporary change in modelled wind direction generated by TAPM has also been assessed for its impact on agreement between modelled and monitored SO_2 concentrations, and an 'idealised run,' where the influence of synoptic winds and their effects on resultant modelled concentrations has shown an expected increase in modelled SO_2 concentrations when these winds are ignored for the same time period. The initial interpretations made in this chapter will now be expanded and discussed further in Chapter 7.

7. Discussion

7.1 Introduction

Modelled concentrations over a two-day period from eight point sources and five different scenarios within the Marsden Point airshed has resulted in no exceedances of the sulphur dioxide National Environmental Standard (NES) for Ambient Air Quality. In fact, modelled 99.9th percentile concentrations from scenario one (all sources) are only 24% of the 1-hour standard of 350µg m^{-3}. Results from the four remaining modelled scenarios are as expected, less, albeit by very little in some cases. Results for scenario two suggest that the Marsden B coal-fired power station would contribute very little to overall concentrations within the airshed. As Mighty River Power has announced in March 2007 its intention to abandon plans to recommission the Marsden B power station, results are of course purely academic, but nevertheless still interesting.

7.2 Model performance

TAPM handles complex terrain by using a terrain-following coordinate system and solving fundamental equations for wind, temperature, moisture, rain, turbulence and pollution dispersion (Bluett *et al*., 2004). This 2-day case study simulation was configured using a 2005 New Zealand data set of terrain, land-use and synoptic scale meteorology. Upwind terrain may have also played a part in the lack of increased concentrations for all plotted scenarios on the hills downwind of the sources, although this is less likely. Upwind terrain can alter the wind flow and turbulence characteristics from those measured at the nearest meteorological station. Hills or rough terrain can change wind speed, direction and turbulence characteristics, and nearby water bodies can considerably dampen turbulence levels (Katestone Scientific, 1998). Hills to the west and south-west of the modelled emission sources (i.e. Ruakaka Forest) range in height from 200 to 260m and there is also the presence of Whangarei Harbour between the emission sources and the more complex topography downwind of the sources.

The simulation of complex environments can result in poor model performance. However, some models will handle complex terrain much more realistically than others. As a result, plume model results must be treated with due caution when terrain effects are significant. Also, in principle, puff models (a non-steady-state Gaussian dispersion model) will produce more accurate results than plume models when terrain effects are significant. Having said that, to assume an advanced model (plume or puff) solves all problems associated with modelling complex terrain would be wrong and the specific conditions of a situation may be simply too

much for all models. This issue highlights the broader concern of choosing the most appropriate model for the required application, and to understand a model's limitations and apply it only to the situations that match its capabilities. Calpuff (an advanced puff model commonly used in New Zealand) modelling outputs tend towards higher concentrations being simulated when complex terrain is involved (US EPA, 1998). This is highlighted by the results contained within a separate modelling study of the Marsden Point airshed that incorporated two large point sources only - the proposed Marsden B power station and the NZRC facility (NIWA, 2004). Results for that study showed greater increases in Calpuff modelled concentrations on the hills downwind of the source emitters compared to this TAPM modelled case study. The simulation time was however vastly different for the two modelling studies - a full-year for the Calpuff study as opposed to the very short two-day period for this TAPM modelled case study. In general, longer runs are more likely to produce more reliable results.

Also, according to the TAPM Version 3 User-Manual (Hurley 2005), a limitation of TAPM is that it cannot be used for very steep terrain because of the use of a terrain-following coordinate system in the model. This approach cannot represent discontinuities in terrain height (for example, cliffs or bluffs). What the user-manual does not define is what constitutes very steep terrain. However, according to Hurley *et al*. (2002), TAPM has been verified in a number of regions of complex terrain and performs well compared to other models, with case-studies for regions throughout Australia. In spite of this limitation, TAPM is widely used throughout New Zealand.

The results of this TAPM case-study indicate that meteorological parameters such as temperature and relative humidity have been predicted with reasonable accuracy for the simulation period, for others such as wind speed and direction less so, being based on results without wind data assimilation. Assistance from local meteorological data may have provided better results and also increased agreement with SO_2 monitoring values. There are several limitations to mesoscle models such as TAPM and of this study specifically, which have been detailed above. Also, this case-study examined a period during winter. A long-term modelling study assessing trends and scenarios over a longer period, say a full year, is likely to be more accurately evaluated and verified using monitored data incorporating all seasons and conditions. Although the Good Practice Guide for Atmospheric Dispersion Modelling (Bluett *et al*., 2004) recommends that case-studies be examined over a period of one to three days with a spatial resolution of 1 to 3 km's as being typical and for an hourly time resolution, the relatively coarse grid resolution used

for this case-study (1 km) may not have provided sufficient spatial resolution for a pollutant such as SO_2 with the potential for high daily spatial variability at finer resolutions.

7.3 Source parameters

Stack height would appear to be the major criterion governing the higher modelled concentrations associated with shipping when compared to higher emitters such as the NZRC and the proposed (abandoned March 2007) Marsden B coal-fired power station (in fact, appropriate stack heights can be determined using dispersion modelling). The downwind topography also no doubt serves to exacerbate the higher modelled concentrations associated with shipping sources due to the lower emission heights. Greater dispersion is achieved when source emissions are emitted at greater height, and this is evident in the individual results for the tallest modelled stacks. Results for both NZRC stacks and the Marsden B stack are substantially lower than the three shipping sources. It is only when shipping emissions at NZRC Jetty 1 are introduced (scenario 4) that modelled output concentrations for NZRC increase. Combined with the number of shipping movements into and out of Whangarei Harbour, particularly those associated with NZRC Jetty 1, the potential for a high contribution from this source to overall concentrations of SO_2 within the Marsden Point airshed is indeed possible, which has been indicated by the modelling results. Keeping in mind the short simulation time, it could be argued that industrial sources within the Marsden Point airshed that have traditionally been highlighted as responsible for the great majority of SO_2 emissions, may well have another prominent source within the airshed to 'point the finger at,' when considering the modelled values from shipping movements within the airshed, particularly at the NZRC jetty. Other stack parameters such as exit velocity, gas temperature and stack diameter and whether or not there is any impedance to the vertical discharge of pollutants, also all play a part in the dispersion of the stack contents and eventual ground-level concentrations.

7.4 Emission rates

Emission rates can also be a major source of error and inconsistency in any modelling analysis. Ideally, emissions information should be sourced from measurements undertaken at the site of interest. Emission rates used in this case study were consent (licence) limits, as issued by the Northland Regional Council for the five industrial point sources modelled (see Appendix 1). Shipping emission rates for SO_2 were calculated using emission factors as presented by Lloyd's Register of Shipping and contained within the Emission Estimation Technique Manual for Maritime Operations Version 1.1 (NPI, 2001). Activities covered in the Manual apply to

facilities primarily engaged in the operation of ports (i.e. the loading and unloading of freight), ballasting, transit, and maintenance and general upkeep of ocean going and inland water vessels. Equations within the manual are used to estimate engine exhaust emissions of pollutants from main and auxiliary engines from port vessels. Equations and other information used to derive model inputs from ship emissions are contained within Appendix 2.

Those with access to ship movement information (Regional Council personnel and the Harbourmaster) into and out of Whangarei Harbour, as well as data pertaining to numbers and sizes of vessels and their associated engines, stack parameters etc., were consulted before calculations were made and model inputs derived. Thorough searching for this information online and in literature failed to find anything of note, and therefore forced the calculation of input data from scratch that has been used here utilising the above mentioned techniques.

7.5 Shipping emissions

Moving goods by ship releases much more sulphur compared to trucking the goods the same distance, and global emissions from ships are increasing. If high modelled SO_2 concentrations from shipping sources berthed in areas such as the Marsden Point airshed are to be believed, what can be done to reduce the exposure of pollutants to populations downwind of the port?

In order to generate electricity for a ship during periods in port, the auxillary engines of the ship are used. Reducing the percentage of sulphur within the fuel when a ship is in berth is one option, and is supposedly the case within the Marsden Point airshed where a 'better quality' fuel is used during this time. One other option of increasing interest around the world is that of shore-side electricity, which can be used to reduce the contribution of shipping to the concentration of air pollutants in ambient air. Basically, a port installs the infrastructure whereby visiting ships can connect to the national electricity grid for the duration of their stay. The costs can be split between the port and the visiting shipping companies, and there will be added benefits in reducing noise when a ship is in berth. The benefits and costs of this option can vary significantly depending on the existing configuration and location of the port, berth and ship (OJEU, 2006).

Whatever option is pursued to reduce emissions from ships in berth in areas where, as in the case of the Marsden Point airshed, residential properties are located downwind of the prevailing wind direction, future likely increases into and out of the Marsden Point airshed by large cargo ships require that a strategy to keep shipping emissions in-check is considered. Although limited in its

scope, the fact that this 2-day modelling case study has returned 99.9th percentile values for shipping emissions (scenario 5) that are 90% of those for all sources (scenario 1) makes this an important decision for those that manage air quality within the Marsden Point airshed.

7.6 New Zealand Refining Company

The New Zealand Refining Company completed alterations to their process resulting in lower levels of SO_2 emissions in 2000. Monitoring results in general have confirmed this reduction compared to years previous to 2000. The lower than initially expected modelling results produced here may, along with other factors previously mentioned, be partly attributable to the alterations to the plant processes. Emission rates as used as inputs for the modelling case study are those contained within the current NZRC resource consent licence for discharge of contaminants into the air (Air Discharge Permit 8319), issued in March 2001 and due to expire in May 2022. The prevailing south-westerly wind direction recorded at the most reliable meteorological station in the area at Whangarei Airport is not the dominant wind direction at Marsden Point where the NZRC is located. On-shore easterlies are the most measured wind direction at this station, and although the Northland Regional Council advises measurements at this station are influenced by objects such as buildings, stacks and oil tankers and therefore not indicative of conditions experienced in the greater Marsden Point area, the recorded easterly has ramifications for areas west of the NZRC site, particularly residential properties in and near the Ruakaka hills, where emissions from the NZRC plant can impact on the elevated terrain of this area during such on-shore wind episodes.

7.7 Modelled v monitored

An important aspect of air dispersion modelling is the relationship between modelled and monitored ground-level concentrations for the same time period. When comparing results from atmospheric dispersion models with measurements it can be difficult to trace the causes of the disagreement because every emission inventory, atmospheric dispersion model and atmospheric measurement contains limitations and inaccuracies. Firstly, the modelled results are based on two days of simulated run-time. Given the time and computing resources, a simulated run-time of one full year utilising on-site acquired meteorological data would have been ideal. However, this is in many cases (as in this case) impractical given the computing time required for such a long-run, so much so that two days where available one-hour concentrations from the Whangarei Heads School monitoring site were chosen instead. It is unfortunate, but performing long-term high-resolution simulations with multiple point sources is simply problematic due to

computational demands at this stage. Examining trends and scenarios can be achieved by longer term modelling periods, but case-studies are typically examined over periods of a few days. Spatial resolutions of 1 to 3 km's are also typical of a case study examination (modelling results reported here are at 1 km resolution) and for an hourly time resolution, as is also the case here. A fifth grid, being the fourth nested grid within the mother domain and with a finer resolution of 300m was run as part of this study for each scenario. However, results for this grid resolution were inconsistent when processing results for 99.9^{th} percentile values and the problem likely lay in the Lagrangian Particle Module (LPM) mode for near-source dispersion having a statistical error. This type of error depends on the number of particles, that is more particles = less statistical (sampling) error. The error can be decreased by increasing the number of particles, which would have also increased the CPU time. At this stage, it was considered sufficient for the purposes of this case study to present results at a coarser, yet acceptable resolution of 1km, which covered a wider geographical extent. As a result, modelled SO_2 values decreased in comparison to the finer grid resolution and also contributed to less agreement with monitored values at Whangarei Heads School.

Another issue worth noting is the lack of finer resolution wind direction data available from the Northland Regional Council. The best resolution available to the Council from records at the Whangarei Airport monitoring site was in blocks of ten degrees, whereas TAPM generates wind direction data at a much finer resolution of one degree. Given this contrast, direct comparisons of the two sets of wind direction data will no doubt result in some discrepancies. Council supplied wind speed data from the Whangarei Airport monitoring site did not suffer from this problem.

A serious constraint to using a prognostic model such as TAPM is that of emissions information, or more to the point, the lack of or great difficulty in obtaining the required information. Being able to access reliable monitoring data to validate the model was also problematic, and the main reason behind choosing the 6^{th} and 7^{th} June 2005 as the time period to be modelled was that one-hour monitoring data was made available for these two days, plus above average levels of SO_2 for these two days had been recorded at a local monitoring site. Twenty-four hour data was also made available, but the aim of the exercise was to compare results with the NES SO_2 standard, which has a one-hour time period attached to it. The 24-hour data was also of decidedly less reliable quality, that is, it was riddled with missing and zero concentration values. Even if the computing time required for an annual run not been an issue, the owners of the largest emissions and monitoring data for the Marsden Point airshed (NZRC) refused to supply the required information. Input data for the model regarding emissions therefore had to be based on consent

(discharge licence) limits issued by the Northland Regional Council, not actual emissions. Where emissions information was available for any of the industrial point sources it was deemed to be of poor quality, although for the most part it was simply not available. Using discharge limits is not necessarily a bad option for model inputs (many companies request dispersion modelling based on emission limits), but actual emissions information may have provided a more accurate picture. In fact, by using inverse modelling techniques, actual emissions could have been calculated if all of the NZRC owned monitoring data had been made available (see Section 7.12). The inclusion of fixed emission rates as contained within the consent limits for the point sources would likely have contributed to the lack of overall agreement between the modelled and monitored data. The use of variable emission rates (hourly), had they been available as inputs for the model, would have provided a far more accurate picture of source emissions and a likely greater alliance with the monitored data. Any uncertainty attached to any of the source emission inputs and meteorological fields, including the mixing height of the lower boundary layer would have conferred less agreement between modelled and monitored values.

Real and accurate emission rates may have also helped decipher the mystery surrounding the large peaks in monitored emissions at the Whangarei Heads School monitoring site, had an industrial source in fact been responsible. In a reporting schedule for the month of June, dated 18th July 2005, NZRC confirm to the Northland Regional Council that "four excursions above the NZ Ambient Air Quality Guideline for sulphur dioxide" had occurred at their Whangarei Heads School monitoring site. "These excursions occurred during a period when meteorological conditions were conducive towards limited dispersion of any emissions of SO_2," and, "we have not excluded the possibility of other potential contributing sources close to the monitor."

Even when those that owned emissions data were enthusiastic at the prospect of dispersion modelling work being carried out within their airshed(s), another problem was encountered. Prior to settling on the Marsden Point airshed as the case study for this research, other Councils were approached and asked if the proposed research was of interest and if emissions and monitoring data would be available. The enthusiasm for the project was never in question regarding any regional authority. The problem was that the required emissions inventory information simply didn't exist, or if it did, was of poor resolution and/or reliability. According to Zawar-Reza, *et al*. (2005), this is indeed the main limitation to progress in the application of prognostic models to air pollution dispersion.

As discussed previously, the abnormally high monitored concentrations at Whangarei Heads School are somewhat of a mystery, but large peaks above the 'normal' are experienced at many monitoring stations and quite possibly every authority in New Zealand in charge of monitoring equipment has experienced this problem at some stage. These anomalies add to the average concentrations of the area of interest and possibly provide a false picture of the air quality associated with the area, particularly when assessing only a couple of days of data. One-off events, including tyre burning, idling vehicles and even rioting, have been supplied as reasons as to why large spikes in concentrations can appear in the monitoring records at sites around the world. Equipment failure is also experienced at monitoring stations and it may be some time before faults are discovered and repaired, but this scenario is more likely to produce zero or missing results rather than large peaks. Another possibility for the high monitored concentrations follows in the next section. The extreme emissions associated with the Whangarei Heads School monitoring site on the days in question cannot be simulated by TAPM in its current configuration, and future progress to incorporate such variation in emissions will be a challenge for model developers.

7.8 Wind and emissions

Considering the plotted wind information for the Marsden A and Marsden Point meteorological stations (Figures 5.2 and 5.4), one would suggest that TAPM has not simulated wind conditions very well for the modelled period. The conditions experienced at these two stations have been included in order to provide an indication of relative influences at each of the stations and the resultant effect of these influences on recorded wind information within the Marsden Point airshed. The Marsden Point meteorological station and its proximity to the elevated terrain on the northern side of the harbour has in the past produced peculiar results according to the Northland Regional Council. Objects such as buildings, stacks and oil tankers are suspected of influencing both wind direction and wind speed. The Marsden A meteorological station is considered more reliable but is not a calibrated station. This site is also subject to ocean-water interface conditions which are unlikely to be representative of the wider Marsden Point area. The Whangarei Airport meteorological monitoring station however conforms to World Meteorological Organisation guidelines for station installation and is deemed by the Northland Regional Council to record conditions that are representative of the wider area and which are not unduly influenced by local topography.

Modelled wind direction (Figure 6.17) for the two-day case-study assessment of the Marsden Point airshed is in general agreement with monitored wind direction at the Whangarei Airport

meteorological monitoring site (Figure 5.8) for the same time period, and both wind roses agree with the synoptic situation being experienced by New Zealand on the dates in question (see Figure 5.10). Wind speed has been overestimated by the model compared to measurements which would have aided modelled dispersion of SO_2 and conferred less agreement with monitored concentrations. However, given the general agreement with wind direction between measurements and model, one could have expected slightly higher agreement between modelled and monitored concentrations of SO_2 at the Whangarei Heads School monitoring site for the simulation period, but the agreement is low. One reason for the disparity (amongst others) may well be explained by the pollution rose contained in Figure 5.25, which elaborates on the fact that large amounts of SO_2 being emitted at the NZRC site do not necessarily correlate with high concentrations of SO_2 being recorded at the school monitoring site. The pollution rose indicates that sources of SO_2 being received at this site may well be emanating from outside the Marsden Point airshed (a south-westerly flow dominated the modelled two-day time period but a north-westerly wind was also recorded in Figure 5.8 for 15% of the time), possibly from industrial zones in and around the city of Whangarei. This result highlights the effects of local meteorology on emissions and the importance of examining meteorology as part of the overall process of assessing compliance of an airshed, and may have important implications for NES policy for both the Marsden Point and Whangarei airsheds. To only inspect the case-study modelling results would suggest compliance of the NES for SO_2 within the Marsden Point airshed for the simulated period, where TAPM has not modelled winds from the north-west at anytime during the simulation period (see Figure 6.17). Monitoring results suggest otherwise (see Figure 6.12). The airshed of interest to this case-study has been the Marsden Point airshed. A review of the Whangarei airshed has not been undertaken as part of this case-study. However, upon contacting the Northland Regional Council, planning is indeed underway to monitor SO_2 levels within the Whangarei airshed (PM_{10} is the NES limiting pollutant), with the purchase of a monitor to be completed by mid 2008. The site of the new monitor is still to be decided, but monitoring site selection within this airshed will no doubt consider that a north-westerly flow is a common wind direction monitored at the Whangarei Airport meteorological station, which is located within the Whangarei airshed. At present under certain wind conditions, it may be a case of the Marsden Point airshed accepting responsibility for emissions of SO_2 outside of its borders and having to also accept the NES related responsibilities of those monitored SO_2 values.

One other interesting aspect of the modelled winds can be seen in Figure 6.20 and which is supported by Figure 5.4, where on-shore east to south-easterly winds have been produced by TAPM during day two of the simulation period and recorded at the Marsden Point

meteorological site as being a dominant wind direction at this station (unlike the Marsden A or Whangarei Airport sites). This on-shore flow may highlight conditions which lead to raised concentrations of SO_2 being found on the elevated terrain of Ruakaka Forest, located west of the Marsden Point area. Unlike the Bream Head Peninsula where residential properties are long established, the residential population of the Ruakaka hills is not as great, but recent subdivision activity resulting in a number of ten acre properties may be the beginning of increased population in the area. This on-shore flow will likely also influence the re-emergence of pollution (re-circulation) returning to the area from earlier in the day or even the previous day, highlighting another issue for pollution levels in the Marsden Point airshed.

7.9 Mixing height and coastal fumigation

New Zealand's varied and interesting topography coupled with the existence of a high percentage of coastal habitation can lead to complex meteorological features in the surroundings of pollution sources. One such feature is that of coastal fumigation, which has the potential to persist for a couple of hours, and in the same location. TAPM is one of several advanced models deemed to provide a realistic representation of the meteorology in a coastal area, and is therefore considered suitable for simulating the fumigation process.

According to the Northland Regional Council, coastal fumigation within the Marsden Point airshed is an uncommon event. However, modelling completed for the Council used to determine the initial location of the new SO_2 monitoring station west of the NZRC site indicated an effect (albeit rare) of coastal fumigation from the refinery in this area and hence one reason to position the site at this location. Also, when considering the appearances of Figures 6.21 (synoptic winds included) and 6.22 (synoptic winds removed), one could suggest that the concentrations (> 100 $\mu g\ m^{-3}$ in the pink shaded areas) associated with the latter are a likely result of plumes from tall (NZRC & Marsden B) on-shore stacks being dragged down by the lower mixing heights associated with flows over water, as opposed to the higher mixing heights associated with flows over land. Mixing heights are higher over land during the day and lower during the night relative to water. The temperature of land fluctuates up and down, whereas for a water body it is constant.

7.10 Deep soil and sea surface temperatures

Default values for soil moisture content and sea surface temperature have been used for the modelling of this case study. Wind speeds near the surface generated by the model can be

affected by variations in the soil moisture content. Differences between high and low soil moisture content affect temperature, which in-turn affects thermal turbulence which leads to lower pressure over the low moisture area than over the high moisture area. This leads to winds flowing from the high pressure zone to the low pressure zone. The greater the difference, the higher the wind speeds (Hirdman, 2006).

Temperature drops caused by coastal upwelling as a result of strong off-shore winds can increase the difference between sea surface and land based temperatures. This not only strengthens the on-shore wind, but also enhances its extent and effect on the coastal air temperature, in-turn influencing the thermal features of the wind (McKendry *et al*., 1988; Hirdman, 2006).

The default values for both soil moisture content and sea surface temperature used here are the climatological averages for the two-day simulation period.

7.11 Background concentrations

Having suitable data on background concentrations is an ideal, but uncommon occurrence. Whilst some may believe that incorporating anything into the modelling process is better than nothing, the quality and validity of available data sets can vary enormously. Natural sources of sulphur dioxide include releases from geothermal activity, including hot springs and volcanic activity, and the natural decay of vegetation on land, in wetlands and in oceans. These sources would have little if any bearing on SO_2 concentrations within the case study airshed.

An SO_2 monitoring site located in a protected or concealed 'cold spot' within the Marsden Point airshed would have been ideal, as would have any meteorological monitoring data from such a site. According to the Northland Regional Council, "Incorporating all sources, an estimate of a typical (annual) background value (averaged across the airshed) would be approximately 3 micrograms per cubic metre. However on any given hour this could vary between 0 and 300 micrograms per cubic metre." Other NZRC SO_2 monitoring sites at Little Munroe Bay and Urquhart's Bay on the Bream Head Peninsula provided average 24-hour values from January 2005 to July 2006 of 1.9 and 1.4 $\mu g\ m^{-3}$ respectively, but this data was riddled with more missing, incomplete and zero values than would be expected of results deemed suitable for modelling inputs (see Figure 5.21). Background concentrations of SO_2 were therefore not incorporated into the modelling for this case study.

7.12 The NES and modelling

Urban-scale air quality models based on prognostic approaches are now accepted as a standard tool in addressing air quality issues. The production of contour maps depicting modelled ground-level concentrations, as contained within the results section of this thesis, can be likened to an exposure map. As well as providing numerical values to assist in *how much* pollution a certain population may be exposed to, the incorporation of meteorological and topographical parameters into the model also provides an indication as to *where* pollution can be expected to occur. This tool can be used to endorse a particular area as being one that may be more prevalent to pollution within the airshed, and therefore aid in the correct siting of compliance monitoring stations as stipulated by the NES. Along with showing where concentrations are likely to occur, the contour map also depicts areas where concentrations are likely not to occur as a result of the modelled sources, which can be helpful in gathering background or natural emissions within an airshed. Areas where populations are known to be exposed to emissions are colloquially known as 'hot spots.' In contrast, areas within an airshed that are deemed via modelling and/or monitoring not to be exposed are known as 'cold spots.' If one 'hot spot' required further investigation, models can also be run at different spatial scales (e.g. street level) and over long or short time scales to assess the effects of chronic or acute exposure.

The correct siting of a SO_2 monitoring station within the Marsden Point airshed will ensure that a representative picture of air quality is captured. From modelling results presented here, it would appear to be an interesting choice of location that the Northland Regional Council initially decided upon for the new NES monitor. Several factors were taken into consideration when the Council selected this first site, just slightly north of due west of the NZRC plant. These included the results of modelling (Calpuff) which noted the rare effect of coastal fumigation from the NZRC in this area. This particular Calpuff modelling study of the combined effects of Marsden B and NZRC (NIWA, 2004) showed the greatest ground level concentrations occurring on the Busby Head Peninsula and between Mt. Lion and Mt. Manaia, the same areas highlighted in this TAPM modelling study as being the most likely to be impacted within the Marsden Point airshed. Fumigation is the mechanism by which pollutants are reapportioned following the break-up of the previous night-time surface based temperature inversion as the lowest layers of the atmosphere warm up in the morning from the heating of the surface. Following the break-up of the inversion, higher layers of air that include the tall stack discharges mix to the ground. The resultant ground level concentrations of the pollutant(s) would make an impact for only an hour or two. For what is a comparatively short period of time, and for a process that occurs only under certain conditions, the use of fumigation as a reason for the initial location of the new NES

monitor was certainly interesting. Expected future development, both industrial and residential, also influenced the Councils decision. However, when assessing the modelled 1-hour maximum SO_2 values from scenario 1 (Figure 6.11), it would appear that the location of the new monitor may be more appropriately sited on the opposite side of the harbour, in a position more akin to that currently being utilised by Whangarei Heads School and Little Munro Bay stations. In fact, the 99.9th percentile values for modelled SO_2 concentrations for all scenarios presented here are not even close to the initial choice of location for the NES monitor, but all follow the expected path across the harbour given the prevailing south-westerly wind direction experienced in the airshed. Having said that, the short simulation time of two days is a major limitation of this analysis and not conducive to accurately assessing trends and scenarios within this airshed. However, although generating higher wind speeds than those recorded at the Whangarei Airport meteorological station, the two days of TAPM generated wind direction (Figure 6.17) does provide general agreement with the wind direction recorded at the Whangarei Airport meteorological station for the case-study simulated period of 6th and 7th June 2005 (Figure 5.8), and therefore provides some justification for the model as well as the suggestion that the NES monitor may be better placed elsewhere. In support of the original location chosen for the NES monitor are the on-shore easterly winds recorded at the Marsden Point meteorological station and which would be measured at this site during these episodes. Despite this, the Northland Regional Council recommends that conditions recorded at the calibrated Whangarei Airport meteorological site are the most reliable and representative of the wider area, and stations already established on the Bream Head Peninsula measuring SO_2 levels are more likely to be located in positions likely to record greater levels of SO_2, as the easterlies recorded at Marsden Point are strong in comparison and more conducive to greater dispersion and lower measured values of SO_2.

The owners of the land where the new NES monitor had been installed (Marsden Deepwater Port) did eventually object to the monitor being located on their land for unspecified political reasons. As a consequence, the decision was made by the Northland Regional Council in late March 2007 to remove and relocate the monitor. The second choice of the Council was to locate the monitor not far from the Whangarei Heads School monitoring site, a site that would appear to be a more appropriate choice given the results of the modelling presented here and for reasons mentioned above. Influencing the Council's decision was the emphasis on the 24-hour guideline as stipulated by the World Health Organisation, and that the new site was better placed to detect elevated concentrations of SO_2, as opposed to the 1-hour peak concentrations associated with fumigation events at the first choice location. It would appear from the limited modelling results

presented here, together with general support from wind direction monitoring at Whangarei Airport, that existing sites (Whangarei Heads School, Little Munro Bay and Urquharts Bay) being used to monitor SO_2 within the Marsden Point airshed are located in the correct areas. The second (enforced) choice of the Northland Regional Council to locate the NES monitor on the opposite side of the harbour to that of the first choice would appear to be a wise decision for reasons already mentioned. If funding ever permitted, the installation of two monitors, one located on the Bream Head Peninsula and one at or near the original designated site would be ideal.

In addition to being a useful tool for estimating population exposure and forecasting spatial variability in the effects on public health, and assisting with site selection for NES compliance monitoring, dispersion modelling can also be used by regional authorities as a tool in assessing the effects of pollution mitigation options and to validate emission reduction strategies for NES compliance (i.e. straight and curved line paths). On the subject of SLiPs and CLiPs, each regional Council within New Zealand was required to develop either a straight line path (SLiP) or a curved line path (CLiP) for any airshed in a region in which the concentration of the limiting pollutant breached the standard. The starting point was based on current and historical monitoring records. For the pollutant of concern (in most cases, PM_{10}, but for the Marsden Point airshed, SO_2), have the results responsible for the start point been recorded at monitoring stations that are representative of air quality in the airshed? Are these records of reliable quality and do greater concentrations occur elsewhere within the airshed away from the monitors? If dispersion modelling, with good quality emissions and meteorological data had been carried out and found to produce higher results for a particular airshed than the monitoring records indicated, should the modelling have been used to determine the starting point?

Another modelling tool available to New Zealand Regional Councils for NES purposes is that of inverse modelling or the back-calculation of pollutant emission rates from monitoring data. All dispersion models rely upon accurate estimates of emission rates. The ability to provide accurate emission-rate estimates for modelling inputs, as we have discovered during this modelling case-study where Northland Regional Council consent licence emission rates have been used, is a major key to providing greater overall agreement between the modelled and monitored SO_2 concentrations in the thesis case-study. Rather than relying purely on monitoring data for a direct assessment of NES compliance, an accurate emission-rate appraisal of the airshed contaminant sources promotes the application of dispersion modelling in predicting compliance within the airshed. This case-study has not performed inverse modelling or back-calculation of SO_2

emission rates from the industrial point sources due to the fact that good quality monitoring information was not made available by the owners of the data, plus the issue of the computational demands of TAPM for such an exercise. Given the time, resources and accurate monitoring information, this could be a worthy subject for a future study to more accurately assess SO_2 concentrations within the Marsden Point airshed.

As we have seen, different models can produce different results. Some models are better at handling the complex topography and meteorology of New Zealand than others. It is therefore probably unwise to rank modelling results above accurate on-site observations. Dispersion modelling is however a good tool to validate the monitoring records and provide confidence (or not) in both.

The modelling process can also be assigned to the selection or reassessment of Local Air Quality Management areas. LAMAs have been defined by patterns of emissions, yet the NES are based on concentration exceedences. As questioned above, is it possible that greater concentrations of pollutants occur away from the monitors within a LAMA, a LAMA which has been designated due to its observed over-stepping of the standard? Do maximum concentrations indeed even occur within a Category 1 LAMA? Due to a lack of observable and/or reliable data, airsheds outside the predominant LAMA deemed not to be a problem by a regional authority due to low emissions may have had their impacts underestimated, as mentioned above in Section 7.8 regarding recorded concentrations of SO_2 within the Marsden Point airshed that may have emanated from outside the airshed. Using concentrations derived from dispersion modelling rather than emissions, LAMA classifications can be revisited and subsequently reconfirmed or updated if required.

Statistical measures show TAPM has simulated the meteorological parameters associated with the two-day simulated case-study of the Marsden Point airshed better than it has concentrations of sulphur dioxide for the same period. Major limitations associated with the case-study have been mentioned, but revolve around the short-simulation period of the case-study brought on by the difficulty in obtaining the required information (both emissions and monitored values) that would have possibly made a longer and more accurate case-study period workable, ignoring of-course the increased computational demands of TAPM for such an exercise. This thesis case-study can therefore confirm that good quality emission inventory data and monitoring results are crucial to the application of modelling as a tool in assessing compliance with the NES, for mitigation and emission reduction strategies and for evaluating the general physical and

chemical progressions responsible for contaminant dispersion and deposition within an airshed. The fact that models such as TAPM require good quality emission inventories, which appear to be limited in availability or simply not exist at all, can however be seen as a negative in the application of mesoscale models such as TAPM to NES related requirements. The case-study also suggests that TAPM may have problems in modelling shorter time averages such as one-hour when limited amounts of input data, such as in this case-study, have been made available. A short simulation period due to limited emission inventory data will effect the amount of error produced by the model.

7.13 Economic consequences of non-compliance with NES

Aside from the serious health consequences for communities who reside in airsheds where air quality has failed to attain the prescribed standard by 1st September 2013, there are potentially significant consequences for a regions economy as well. Indeed, the risk of damage to the national economy is also a potential consequence of non-compliance. Resource consents, or discharge licences, will not be granted in a particular airshed if more than one exceedence results in future years. In fact, non-complying areas can be denied discharge licences before 2013 if an activity causes exceedences of the straight-line path for the relevant limiting pollutant. Several New Zealand cities and towns regularly exceed the standards, particularly that for PM_{10}. Resource consents for discharges to air could also be affected by the NES regulations when a renewal is sought by existing consent holders. On the other hand, positive economic consequences may eventuate for areas where the relevant standard has been attained through attracting and retaining businesses that may be unable to operate where the standards have been breached.

Applying changes to the methods people use to heat their homes and how businesses produce their goods in efforts to reduce emissions and to meet the requirements of the NES could also result in economic hardship. For example, if more efficient wood burners that produce less particulate emissions are deemed to be too expensive for the average household (or are not available), some may be forced to change to more expensive energy sources such as electricity and gas in order for the airshed to meet the standards. As a country where power shortages are often a topic of debate, does the infrastructure exist in New Zealand to meet an increase in energy demand if people move en masse to alternative methods of heating their homes? Increasing the infrastructure to service such a need could impact negatively on energy prices paid by consumers.

Of course, the health implications of non-compliance themselves have a negative economic impact. The financial losses to a non-complying airshed in terms of medical expenses, lost time and productivity and other health-related factors could be substantial, particularly in the long-term. While there are no doubt many positive elements associated with a region's expanding economy, there will undeniably be many challenges in striving to balance the benefits of growth with the environmental and public health pressures that increased activity creates.

The consequences of non-compliance with the ambient air quality standards could be significant. On-going health issues and limited future economic expansion could seriously undermine the long-term stability and prosperity of a region, and quite possibly may also impact at a national level. The new standards may be difficult to meet for some airsheds that have historically exceeded the imposed values, impossible in some cases if World Health Organisation guidelines are ever introduced as standards (see below), without shutting down new development altogether or curtailing some existing economic activity. The benefit-cost ratio required to achieve acceptable exposure levels and avoid the negative economic development and health related implications of poor air quality in an increasingly progressing environment, will require skilled air quality management by New Zealand regional authorities.

7.14 NES challenge

One challenge for the setting of standards for ambient air quality in New Zealand is that of consistent review and updating of contaminants and values contained within the standards. In October 2006, the World Health Organisation (WHO) issued its new Air Quality Guidelines with dramatically stricter values for concentration levels of pollutants. Interim targets have been outlined for each pollutant as a pathway to meeting the relevant guideline. For sulphur dioxide, the guideline level was reduced from 125 to 20 $\mu g\ m^{-3}$ over a 24-hour time period. The present day New Zealand 24-hour SO_2 guideline is 120 $\mu g\ m^{-3}$. As can be seen when viewing a graph such as that contained in Figure 5.21, 24-hour monitored concentrations at the three Bream Head Peninsula SO_2 monitoring stations highlight that a reduction to 20 $\mu g\ m^{-3}$ within the Marsden Point airshed would be a particularly tall order, particularly at the Whangarei Heads School site.

It would be prudent for the New Zealand air quality standards to be reviewed periodically to account for advances made both locally and internationally in the research of health related effects of contaminants, for the values associated with existing pollutant standards and for the number of pollutants contained within the standards.

8. Conclusion

Air pollution represents one of the most challenging issues facing modern day humanity. With unprecedented economic growth of developing countries leading to an increase in the demand for energy and other environmental resources, the prevention of air degradation by means of controlling atmospheric emissions has become a necessary responsibility. The mitigation strategies for traditional but persistent air pollution problems are also becoming an increasingly important issue. Having regulations that will be enforceable by law will drive the required changes much faster than those attainable through voluntary targets alone. Science has a crucial role to play in the projection, interpretation and mitigation of atmospheric pollution phenomena. The need for the general population to have an understanding, or at least awareness, of the process of policy implementation is also of prime importance for the successful performance of air quality legislation.

In New Zealand, the realisation of national standards for air quality coupled with recent studies attributing elevated air pollution to tangible and grave health consequences for communities has brought attention to air quality management issues. The New Zealand National Environmental Standards (NES) for Ambient Air Quality came into force on 1st September 2005. To be fully implemented by September 2013, the standards emanated from previous inconsistencies in air quality management across New Zealand and were also designed to improve the workings of the Resource Management Act (RMA). The Air Quality standards apply in the open, everywhere where people may be exposed and require monitoring to be carried out where the standards are most likely to be exceeded. This legislation has broad and far-reaching implications for resource managers, resource users and possibly the economy of individual regions and the country as a whole.

This study has utilised atmospheric dispersion modelling techniques as a tool for assessing the impacts associated with the only SO_2 limited New Zealand regional authority airshed, comprising several industrial point source emitters plus those emissions associated with shipping in the area. Dispersion modelling is a challenging task in coastal regions or complex terrain, both of which are relevant to the case study airshed. The requirements associated with a thorough modelling assessment comprising high temporal and spatial resolution for an extended period of simulated time have been unattainable for this particular case-study, due to a lack of good quality emissions and monitoring information and the computational requirements associated with such an endeavour, resulting in a case-study of limited effectiveness. The simulated two-day case study presented here has returned 99.9th percentile and maximum values within those stipulated

by the air quality standards for sulphur dioxide, but with certain simulations also showing that raised concentrations of SO_2 can occur over the higher and predominantly downwind terrain of the Bream Head Peninsula. An extended simulation time with scrutiny of trends and incorporating specialised scenarios would likely provide greater clarity as to the levels which sulphur dioxide can attain within the Marsden Point airshed. A project concentrating solely on the emissions from shipping within the airshed would also be justified given the contribution of this source to the overall modelling results produced in this case study. Although modelled values are within the limits set by the standards, the Northland Regional Council should continue to strive to maintain good air quality and, if possible, reduce emissions.

Measured meteorological conditions within the Marsden Point airshed vary from station to station and, as they do anywhere, have a critical influence on how much and where sulphur dioxide values of concern will occur within the airshed. Modelled wind direction for the simulation period has general support from the most reliable recording site in the area, but TAPM has failed to predict wind conditions that are consistent with measured values during an important phase of the case-study period, and consequently failed to produce pollutant values that agree with actual measurements. Wind speed has also been over-estimated by the model.

There are however valid reasons for choosing a modelling tool to assess the implementation of the NES:

- an understanding of the spatial and temporal variation in air pollution can be provided by models;
- models can be used to predict future ambient air pollution concentrations in response to a range of different air quality management strategies, aiding in the confidence and accuracy of designated straight line (SLiPs) and curved line (CLiPs) paths;
- models can be used to define and update airsheds (LAMAs);
- the association between concentrations and emissions can be provided through predictive dispersion modelling, linking LAMAs (defined essentially by patterns of emissions) and the Standards (based on extreme concentrations);
- applications in long-term epidemiological studies of human exposure to air pollution can be provided by models;
- models can aid in the correct siting of compliance monitoring stations as stipulated by the NES.

With regard to the prognostic modelling approach utilised here, it would appear the chief obstruction to continued and increased usage of such models for air pollution dispersion assessment is that of the unsatisfactory availability and integrity of emission inventories and monitoring data to validate modelling results, and which in this modelling case-study was a major reason for simulating a very short time period and ultimately a considerable limitation to a more thorough evaluation of sulphur dioxide levels in the Marsden Point airshed. The inclusion of fixed emission rates for the modelling of the case study point sources has likely contributed to the lack of overall agreement between modelled and monitored data. Greater alliance with the modelled results would have likely been achieved with variable emission rates had they been available as inputs for the model. Uncertainty attached to any of the source emission inputs will likely confer less agreement between modelled and measured values. That TAPM (and other models) requires good quality emission inventories, which appear to be very limited in their availability following approaches to several New Zealand Regional Councils, can be viewed as a negative in the application of mesoscale models to NES related requirements, and could discourage their use for Councils with limited resources and untrained staff, particularly when the computational demands of such complex models are taken into account, this being another critical reason for the short two-day case-study simulation. The importance of examining dispersion modelling results in conjunction with the meteorology of an airshed is also of critical importance as part of the overall process of assessing compliance of a NES airshed.

However, the prognostic modelling approach is increasingly being used as a tool to address air quality issues in New Zealand, and will continue to be in the appraisal of emission reduction scenarios for NES compliance. The concept of exposure mapping as a result of the modelling process will no doubt also become a crucial tool for the management of air quality within a regional authority's domain. The issue of choosing the most appropriate model for the required application, and understanding a model's limitations and applying it only to the situations that match its capabilities will also contribute to the successful use of modelling and its contributions to the NES process. A quote attributed to an anonymous source however suggests that "models are designed to be used, not necessarily believed," and this reinforces the fact that there will always be the requirement for more and better quality monitoring. The continuity of reliable contaminant measurements, from both anthropogenic and natural (background) causes, is vital to a thorough understanding of an airsheds pollution levels and will aid in the selection of appropriate mitigation options. Models are an approximation to reality and possess the ability to complement measurements, but should not replace them. The integration of modelling and measurements, coupled with an understanding of the mechanisms of interaction between

meteorology and emissions and their relative roles in influencing ambient pollution concentrations are fundamentally important activities for air quality management in general, and for the successful implementation of the National Environmental Standards for Ambient Air Quality in New Zealand.

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Appendices

Appendix 1 - Point source emitters and stack input parameters for model

Introduction

Eight sources, including five industrial plus three associated with shipping activities have been used as point sources to be modelled using TAPM for the thesis modelling case-study of the Marsden Point airshed. Consent limits, as issued by the Northland Regional Council, have been used as stack parameter inputs required by TAPM. These are detailed below.

1. Stack A (NZRC Refinery) emissions:
    a) Stack location: 35 50 25.6013 S 174 29 38.8293 E
    b) Model coordinates: -35.840 174.494
    c) Stack height: 100m
    d) Stack exit diameter: 2.6m
    e) Exit temperature: 200°C (473.15 K)
    f) Exit velocity: 28 m s^{-1}
    g) SO_2 emission rate: 2.3 g s^{-1}

2. Stack B&C (NZRC Refinery) emissions:
    a) Stack location: 35 50 35.6312 S 174 29 36.1077 E
    b) Model coordinates: -35.843 174.493
    c) Stack height: 121m
    d) Stack exit diameter: 4.1m
    e) Exit temperature: 210°C (483.15K)
    f) Exit velocity: 22 m s^{-1}
    g) SO_2 emission rate: 137 g s^{-1}

3. Blacktop asphalts (14MW asphalt plant):

a) Stack location: 35 50 35.3349 S 174 29 10.2726 E
b) Model coordinates: -35.843 174.486
c) Stack Height: 10m
d) Stack exit diameter: 1.0m
e) Exit temperature: 170°C (443.15K)
f) Exit velocity: 12.8 m s^{-1}
g) SO_2 emission rate: 2.2 g s^{-1}

4. Carter Holt Harvey LVL plant (Wood fired boiler):

a) Stack location: 35 51 07.0180 S 174 28 56.5525 E
b) Model coordinates: -35.852 174.483
c) Stack height: 25m
d) Stack exit diameter: 1.7m
e) Exit temperature: 90°C (363.15K)
f) Exit velocity: 10 m s^{-1}
g) SO_2 emission rate: 0.09 g s^{-1}

5. Marsden B (300MW):

a) Stack location: 35 50 25.9551 S 174 29 39.3163
b) Model coordinates: -35.840 174.494
c) Stack height: 120m
d) Stack exit diameter: 4.3m
e) Exit temperature: 85.7°C (358.85K)
f) Exit velocity: 24.2 m s^{-1}
g) SO_2 emission rate after Flue Gas Desulphurisation: 90 g s^{-1}

6. Marsden Port:

a) Stack location: 35 49 55.2358 S 174 29 11.6768 E
b) Model coordinates: -35.832 174.486
c) Stack height: 30m
d) Stack exit diameter: 1.0m
e) Exit temperature: 325°C (598.15K)
f) Exit velocity: 15 m s^{-1}
g) SO_2 emission rate: 48.82 g s^{-1}

7. NZRC Jetty 1:

a) Stack location: 35 50 07.5747 S 174 29 52.9990E
b) Model coordinates: -35.835 174.498
c) Stack height: 30m
d) Stack exit diameter: 1.0m
e) Exit temperature: 325°C (598.15K)
f) Exit velocity: 15 m s^{-1}
g) SO_2 emission rate: 60.25 g s^{-1}

8. Transit point off Home Point (for ships in transit through the harbour en route to other ports - Port Whangarei or Golden Bay Cement - not in Marsden airshed):

a) Stack location: 35 50 01.0239 S 174 30 02.9991 E
b) Model coordinates: -35.834 174.501
c) Stack height: 30m
d) Stack exit diameter: 1.0m
e) Exit temperature: 325°C (598.15K)
f) Exit velocity: 15 m s^{-1}
g) SO_2 emission rate: 33.07 g s^{-1}

Appendix 2 - Shipping emission equations and calculations

Introduction

Equations 3 and 4 (below) can be used to estimate engine exhaust emissions of pollutants from main and auxiliary engines respectively from relevant port vessels. Emissions can then be calculated for each pollutant of interest by summing the number of main and auxiliary engines in operation. Calculations resulting in shipping emission inputs for the Marsden Point airshed modelling case-study are detailed.

Table A1 shows Emission Coefficients for Equation 3 and Equation 4 as presented by Lloyd's Register of Shipping, and contained within the Emission Estimation Technique Manual for Maritime Operations Version 1.1 (NPI, 2001). Table A2 lists the correction factors for Equation 3 and Equation 4, which are used in order to account for the sulphur content of the fuel. These factors and/or equations can be used for estimating emissions from harbour and port vessels, such as tugs and safety vessels and larger vessels in port.

Equation 3

Emain = 0.001 * q * Pr *N

where:

Emain = emissions from main engines (kg hr^{-1})

q = emission coefficient (from Table A1 below)

r = emission coefficient (from Table A1 below)

Pr = engine power (kW) multiplied by engine load

N = number of engines

Equation 4

Eaux = 0.001 * s * At * C

where:

Eaux = emissions from auxiliary engines (kg hr^{-1})

s = emission coefficient (from Table A1 below)

t = emission coefficient (from Table A1 below)

A = auxiliary power (assume 600kW for all vessels)

C = factor to account for sulphur content in fuel (from Table A2 below)

Table A1. Emission Coefficients for Equation 3 and Equation 4 (source: NPI, 2001).

Substance emitted	Main Engines		Auxiliary Engines	
	q	r	s	t
Oxides of nitrogen	Medium - 4.25 Slow - 17.5	Medium - 1.15 Slow - 1.00	4.25	1.15
Carbon monoxide	Medium - 15.32 Slow - 0.68	Medium - 0.68 Slow - 1.08	15.32	0.68
Sulphur dioxide	Medium - 2.31 Slow - 11.34	Medium - 1.00 Slow - 1.00	2.36	1.00
PM_{10}	Medium - 0.11 Slow - 0.93	Medium - 1.00 Slow - 1.00	0.11	1.00
Volatile organic compunds (VOCs)	Medium - 4.86 Slow - 0.28	Medium - 0.69 Slow - 1.00	4.86	0.69

Table A2. Correction Factors (C) for Equation 3 and Equation 4 (source: NPI, 2001).

Gross Tonnage of Vessel	Correction Factor - C
<1000	1
1000 - 5000	2
5000 - 10000	3
10000 - 50000	4
>50000	5

Shipping emission calculations - Marsden Point airshed modelling case-study:

1. Marsden Port

$E_{main} = 0.001 * q * Pr * N$

$= 0.001 * 11.34 * (15000)^{1.00} * 1$

$= 170.1 \text{ kg } SO_2 \text{ hr}^{-1}$

$= 47.25 \text{ g s}^{-1}$

$E_{aux} = 0.001 * s * A^t * C$

$= 0.001 * 2.36 * (600)^{1.00} * 4$

$= 5.66 \text{ kg } SO_2 \text{ hr}^{-1}$

$= 1.57 \text{ g s}^{-1}$

Total emissions: $E_{main} + E_{aux} = 47.25 + 1.57 = 48.82 \text{ g s}^{-1}$

2. NZRC Jetty 1

E_{main} = 0.001 * q * Pr *N
= 0.001 * 11.34 * (18500) $^{1.00}$ * 1
= 209.79 kg SO_2 hr $^{-1}$
= 58.28 g s $^{-1}$

E_{aux} = 0.001 * s * A^t *C
= 0.001 * 2.36 * (600) $^{1.00}$ * 5
= 7.08 kg SO_2 hr $^{-1}$
= 1.97 g s $^{-1}$

Total emissions: $E_{main} + E_{aux}$ = 58.28 + 1.97 = 60.25 g s $^{-1}$

3. Transit point within harbour

E_{main} = 0.001 * q * Pr *N
= 0.001 * 11.34 * (10000) $^{1.00}$ * 1
= 113.4 kg SO_2 hr $^{-1}$
= 31.5 g s $^{-1}$

E_{aux} = 0.001 * s * A^t *C
= 0.001 * 2.36 * (600) $^{1.00}$ * 4
= 5.66 kg SO_2 hr $^{-1}$
= 1.57 g s $^{-1}$

Total emissions: $E_{main} + E_{aux}$ = 31.5 + 1.57 = 33.07 g s $^{-1}$